Forest Research Report No. 165

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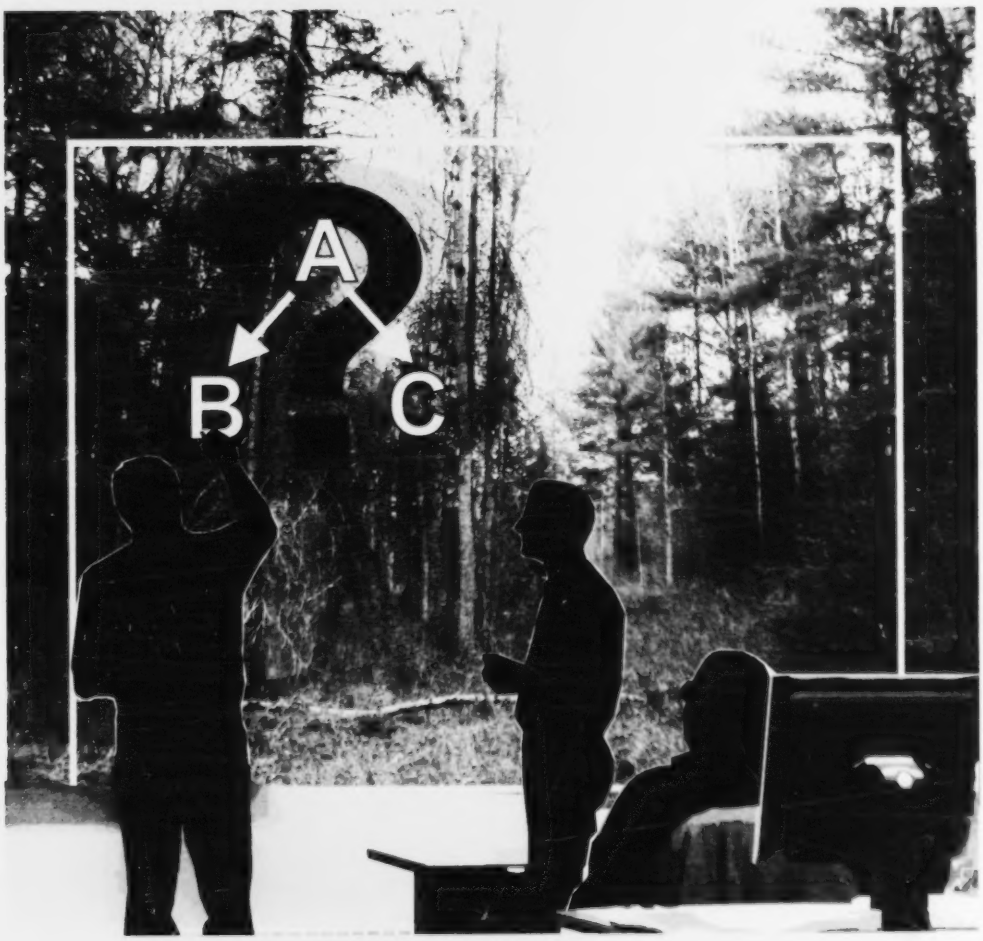
of boreal forest succession in Ontario through a workshop approach



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Identifying uncertainty in practitioner knowledge of boreal forest succession in Ontario through a workshop approach

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Abstract

Expert knowledge of boreal forest succession is used widely in forest management in boreal Ontario, but the level of uncertainty of this mainly implicit knowledge is unknown. Therefore, in this study expert knowledge of boreal forest succession was elicited, its uncertainty quantified, and the sources of this uncertainty investigated.

During two multi-day expert workshops in Ontario's Northwest and Northeast Region, groups of forestry experts reviewed available expert knowledge of post-fire establishment and natural succession. After confirming or adapting the available knowledge, experts estimated their confidence in the knowledge and perceived knowledge complexity. Estimates of confidence and complexity were combined to quantify individual expert knowledge uncertainty. Among-expert variability was quantified as an estimate of collective expert uncertainty in succession knowledge. Individual expert uncertainty and collective expert uncertainty were combined to quantify composite expert uncertainty. The levels of these components of knowledge uncertainty were investigated and associations of confidence, complexity, and collective expert uncertainty with forest cover type and site conditions assessed.

Expert confidence in forest succession knowledge and perceived complexity of the knowledge were mainly medium, leading to high individual uncertainty. Collective uncertainty tended to be lower for post-fire establishment than for natural succession knowledge, leading to lower composite uncertainty for post-fire establishment. Components of knowledge uncertainty were less often associated with forest cover type and site conditions for post-fire establishment than for natural succession, possibly because local factors are less important for vegetation dynamics immediately after fire. Components of knowledge uncertainty were most often associated with standard forest unit, but no clear pattern among forest units emerged. Components of uncertainty were also associated with leaf type, tending to be lower for coniferous forest units than for hardwood and mixedwood forest units, and they were occasionally associated with site conditions, tending to be lower for dry or saturated and poor or organic sites than for moderate sites.

Our results indicate that uncertainty of forest succession knowledge in Ontario is variable, but often high, and can sometimes be related to ecological factors. We propose that a decrease in the existing knowledge uncertainty would increase forest management effectiveness.

Résumé

Évaluation, dans le cadre d'ateliers, de l'incertitude des experts quant à leurs connaissances concernant la succession dans la forêt boréale de l'Ontario

Le savoir de l'expert concernant la succession de la forêt boréale est grandement exploité dans la gestion forestière en Ontario, mais le niveau d'incertitude quant à ce savoir principalement implicite n'est pas connu. Par conséquent, dans cette étude, le savoir des experts sur la succession de la forêt boréale est mis au jour, son incertitude quantifiée, et les sources de cette incertitude examinées en profondeur.

Au cours de deux ateliers de plusieurs jours qui se sont tenus dans la Région du Nord-Ouest et du Nord-Est, des groupes d'experts de la forêt ont examiné la connaissance experte disponible sur la composition forestière post-incendie et la succession naturelle. Après avoir confirmé ou adapté les connaissances disponibles, les experts ont évalué leur confiance dans leurs connaissances et la complexité perçue de ces connaissances. Les estimations de la confiance et de la complexité ont été combinées pour quantifier l'incertitude sur les connaissances chez chaque expert. La variabilité d'un expert à l'autre a été quantifiée en tant qu'estimation de l'incertitude collective des experts sur leur savoir concernant la succession forestière. L'incertitude de chaque expert et la variabilité d'un expert à l'autre ont été combinées pour quantifier le taux d'incertitude composite des experts. On a ensuite examiné en profondeur les niveaux de ces éléments de l'incertitude et analysé dans quelle mesure la confiance, la complexité et l'incertitude collective des experts étaient associées avec le type de couverture forestière et l'état des sites.

La confiance des experts dans leurs connaissances sur la succession forestière et la complexité perçue de leurs connaissances se sont révélées être moyennes, avec pour résultat un taux élevé d'incertitude chez chaque expert. L'incertitude collective a tendance à être plus atténuée pour les connaissances sur la composition forestière post-incendie que pour celles sur la succession naturelle, ce qui donne un taux d'incertitude composite plus bas pour la composition forestière après incendie. Par ailleurs, les éléments de l'incertitude sur les connaissances sont moins souvent associés avec le type de couverture forestière et l'état des sites pour la composition après incendie que pour la succession naturelle, possiblement parce que les facteurs locaux sont moins importants pour la dynamique végétale immédiatement après un incendie. Les éléments de l'incertitude sont le plus souvent associés avec l'unité forestière standard, mais aucune tendance claire parmi les unités forestières n'a émergé. Les éléments de l'incertitude ont été aussi associés avec le type de feuillage, l'incertitude étant généralement plus atténuée pour les unités de résineux que pour les unités de feuillus et de forêt mixte. Les éléments de l'incertitude ont été occasionnellement associés avec l'état des sites, l'incertitude étant généralement plus faible pour les sites secs ou saturés et médiocres ou organiques que pour les sites moyens.

Nos résultats indiquent que l'incertitude des experts quant à leurs connaissances sur la succession forestière en Ontario varie, mais qu'elle est souvent élevée, et qu'elle peut parfois être reliée à des facteurs écologiques. Nous avançons qu'une réduction de l'incertitude quant au savoir expert existant accroîtrait l'efficacité de la gestion forestière.

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Executive summary

Knowledge of forest succession is an important part of the knowledge base used for forest management in boreal Ontario and is mostly expert knowledge held by forest practitioners. This expert knowledge is mainly acquired in an informal manner and seldom thoroughly documented or explicitly quantified. Therefore, the uncertainty of this knowledge cannot be readily assessed and the knowledge itself is at risk of being lost. A research study was developed with the broad goal of documenting expert knowledge of boreal forest succession in Ontario, assessing its uncertainty, and increasing its reliability. This report documents the first phase of this study with the objectives of (i) eliciting latent expert knowledge of boreal forest succession, (ii) quantifying its uncertainty, and (iii) investigating the sources of this uncertainty.

Expert knowledge of boreal forest succession in Ontario has been semi-formally captured as suggested succession rules. These rules are quantifications of the probabilities of forest stands to succeed from one forest cover type to another after disturbance by fire or through natural succession. Site-specific formulations of these succession rules are seldom evidence-based and mostly best guesses.

Knowledge uncertainty consists of two main components; (i) the uncertainty of an *individual* and (ii) the uncertainty of a *collective* of individuals. *Individual* uncertainty itself also has two dimensions: (i) *confidence* in knowledge and (ii) *complexity* of knowledge. Combining *individual* and *collective* uncertainty provides an estimate of *composite* uncertainty.

During two multi-day expert workshops in Ontario's Northwest and Northeast Region expert knowledge of boreal forest succession was elicited and its uncertainty assessed. Groups of forestry experts reviewed suggested rules for post-fire establishment and natural succession. After confirming or adapting the suggested rules, experts estimated their confidence in and perceived complexity of the knowledge. Confidence and complexity were combined to quantify individual knowledge uncertainty. Among-expert variability in knowledge was quantified as an estimate of collective uncertainty. Individual uncertainty and collective uncertainty were combined to estimate composite uncertainty. We investigated the levels of all components of knowledge uncertainty and assessed the associations of confidence, complexity of knowledge, and collective uncertainty with forest cover type and site conditions.

- Expert confidence and perceived complexity were mainly medium, leading to high individual uncertainty in the Northwest Region and low or high individual uncertainty in the Northeast Region.
- Collective uncertainty tended to be lower for post-fire establishment than for natural succession knowledge, leading to medium to high composite uncertainty for post-fire establishment knowledge and to high composite uncertainty for natural succession knowledge.
- Elements of knowledge uncertainty for post-fire establishment were less often associated with forest cover type and site conditions than was the case for natural succession, possibly caused by decreased importance of local factors for vegetation dynamics immediately after fire.
- Confidence, knowledge complexity, and among-expert variability were associated with standard forest unit, but no clear pattern among forest units emerged.
- Knowledge complexity and among-expert variability were associated with leaf type tending to be lower for coniferous forest units than for hardwood and mixedwood forest units.
- Knowledge complexity was associated with site conditions, tending to be lower for dry or saturated and poor or organic sites than for moderate sites.
- Components of knowledge uncertainty were less often associated with forest cover type and site conditions in the Northwest Region than the Northeast Region, possibly because of less variation in site conditions of succession rules reviewed in the Northwest Region and differences between knowledge elicitation processes.

Our results indicate that uncertainty of boreal forest succession knowledge in Ontario is variable, but mainly high. If forest management continues without factoring in this uncertainty in forest succession knowledge, the effectiveness of management activities may be decreased. Therefore, we propose that research that reduces knowledge uncertainty of boreal forest succession be supported, and in areas where knowledge uncertainty cannot be reduced, it should explicitly be incorporated into forest management. Both decreasing knowledge uncertainty and/or explicitly incorporating it in forest management would increase forest management effectiveness.

This report consists of four main parts:

In the introduction, we give examples of the use of forest succession knowledge in forest management in boreal Ontario. We explain that much of this knowledge is expert knowledge, how that expert knowledge is created, and what the main characteristics of this expert knowledge are. Finally, we place this study in the context of the larger research project and explain its objectives.

In the *methods* section, we provide background information about the concept of knowledge uncertainty and possible assessment methods. We then describe characteristics of experts and how their knowledge can be elicited. The background section ends with specifics about the application of forest succession expert knowledge in Ontario. Then, we detail the characteristics of the participating experts and the method of knowledge elicitation used in this study, specified by region where necessary. Subsequently, we describe the methods used to assess the various components of knowledge uncertainty. Finally, we describe the methods of data transformation and statistical tests. The methods section is somewhat technical and can be skipped by the time-pressed reader.

In the *results* section, we detail the quantification of the various components of uncertainty, beginning with the Northeast Region. For each component, we describe the distribution of uncertainty and determine whether it is generally low, medium, or high. Where applicable, this is followed by a description of the association of this component with transition rule characteristics, i.e., forest cover type and site conditions. These sections are followed by the components of uncertainty for the Northwest Region, similarly presented. These sections are very detailed and the time-pressed reader may skip to the final section of the results where the main findings are summarized.

In the *conclusions* section, we present strengths and weaknesses of this study and discuss implications of the study results for forest policy and management in Ontario.

The main body of the text is followed by *appendices* containing detailed information about the timing of various stages in the study, the knowledge elicitation protocol used during the workshops, lists of forest succession rules selected by regional experts for review during the workshops, and succession rules reviewed by the regional experts listed by region, succession type, and expert.

1. Introduction

1.1. Forest management and forest succession in Ontario

Most of the managed forest landscape in Ontario, which exceeds 45 million ha (OMNR 2002), is disturbance-driven with fire being the primary disturbance. These periodic large-scale fire disturbances initiate a complex series of forest composition dynamics by destroying extant cover, resulting in its subsequent re-establishment followed by gradual transitions in forest composition. Knowledge of these forest cover transitions, commonly referred to as forest succession, is essential for understanding possibilities of future forest cover states, as well as guiding forest composition towards desired future states through management. Consequently, the value of forest succession knowledge is widely recognized by the Ontario Ministry of Natural Resources (MNR), as reflected in its use in a range of guides and directives that regulate forest management.

These guides and directives include habitat guidelines for several species, for example pileated woodpecker (Naylor et al. 1996), marten (Watt et al. 1996), and white tailed-deer (Voigt et al. 1997), which identify the need for planning towards specific forest cover composition to provide preferred habitat. Many other policy documents make explicit reference to tree species composition and successional processes. For example, following are excerpts from recent policy documents, both strategic and operational, that state the value of knowledge of forest cover transitions resulting from natural disturbances for aspects of forest management:

> ***Wilderness policy*** (OMNR 1997): *Wherever possible, management policies are directed toward achieving minimum human intervention and the maintenance of natural vegetation succession patterns*
>
> ***Old growth policy*** (OMNR 2003): *The conservation of representative old growth ecosystems in each ecoregion can be based on an assessment of natural disturbances and landscape patterns for a projected period of time, which removes all human influences. … The results should include the following: probabilities for natural variation in landscape ageing patterns, species occurrence (area in hectares), and distribution in each ecoregion*
>
> ***Forest management planning manual*** (OMNR 2004a): *Large, healthy, diverse and productive Crown forests and their associated ecological processes and biological diversity should be conserved … the long-term health and vigour of Crown forests should be provided for by using forest practices that, within the limits of silvicultural requirements, emulate natural disturbances and landscape patterns while minimizing adverse effects …*

At the same time, the inadequacy and uncertainty of the current knowledge of forest landscape dynamics and successional processes and the need to improve the present state of knowledge for boreal Ontario is recognized. For example, the need for better knowledge of forest succession is expressed in the Provincial Wood Supply Strategy (OMNR 2004b): *The ability to accurately predict wood supply is limited by the quality of the information on which we base wood supply projections within forest management planning … more accurate resource inventory and increased knowledge of forest succession will allow for improved decisions concerning the scheduling of forest stands for harvesting.* As well, a recent forestry workshop that focussed on Ontario's wood supply identified the need for improved knowledge of forest succession at various stages of stand development as one of the knowledge gaps that need to be addressed to reduce uncertainties in wood supply predictions (Sobze et al. 2006).

All of this points towards the need for more reliable knowledge of forest succession to support forest management in Ontario, which first requires a clear understanding of the state of forest succession knowledge – its use and characteristics.

1.2. Applications of expert knowledge of forest succession

Much of the knowledge about forest succession used for forest management in boreal Ontario is knowledge that resides with experienced forest practitioners – mostly forest managers and ecologists from both public and private sector. Thus, for this study, we deem forest practitioners to be the experts and refer to them as such throughout. The following examples illustrate the current use of expert knowledge about forest succession in scoping and exploration, policy development, and forest management planning.

An example of the application of expert knowledge in scoping and exploration is the use of expert knowledge about forest succession in combination with scientific data in a Canadian Ecology Centre-Forestry Research Partnership workshop to advance the understanding of the allowable cut effect in relation to intensive forest management (Newton 2001).

The use of expert knowledge in strategic policy development is exemplified by MNR's new landscape guide for forest management and wildlife habitat provision, scheduled for release in 2007. This guide is based in part on studies that utilize expert knowledge. For example, probabilities of future forest landscape patterns and processes that are incorporated into the guide are generated using the Boreal Forest Landscape Dynamics Simulator (BFOLDS, Perera et al. 2003). The forest succession rules used by BFOLDS to forecast future forest landscape states for the purposes of the landscape guide were generated by forestry experts from MNR's Northeast and Northwest Regions and are largely based on expert knowledge about boreal forest succession.

An example of the use of expert knowledge in forest management planning is applying the Strategic Forest Management Model (SFMM, Davis 1999) to explore consequences of alternative management strategies during harvest planning in northern Ontario. Expert knowledge has been the basis for formulating succession rules applied in SFMM to forecast future forest in all forest management units throughout northern Ontario for nearly a decade.

The tactical use of expert knowledge of forest succession occurs during operational forest management decision-making, such as developing silvicultural prescriptions at the free-to-grow stage for desired future states, and predicting trajectories of complex forest stands such as boreal mixedwoods.

Given the reliance on expert knowledge in forest management policy, planning, and operations, can this knowledge be characterized? Below we describe some of the characteristics of expert knowledge, especially as relevant to forest succession.

1.3. Characteristics of expert knowledge

Expert knowledge of forest succession is acquired by forest practitioners primarily through practical experience and observations in combination with information gathered from formally published literature as well as many informal sources such as knowledge exchange with colleagues. While expert knowledge of forest succession may be formed in many ways, it primarily involves the acquisition and synthesis of implicit knowledge about forest stand dynamics. This process is casual, unplanned, and heuristic, and requires a certain degree of confidence on the expert's part. When experts acquire this knowledge, they may simplify it by filtering out information they feel is not relevant based on their own abstraction of the inherent processes (Fazey et al. 2006).

One simplification that experts resort to during this filtering stage is deriving discrete forest cover types and spatially discrete forest stands from the complex assortment of site types, age groups, and species compositions. For example, they would assume that, once delineated, stands are homogenous within, i.e., variation through the entire forest is accounted for by variation among stands and not by variation within stands. As well, among-stand boundaries are assumed to be spatially discrete, rather than continuous with spatial gradients. Furthermore,

stands are grouped into a limited number of discrete forest cover types, based on species composition, structure, and/or productivity. While experts may simplify the above processes for knowledge acquisition, they are likely to remain cognizant of the inherent complexity of those processes.

When experts formulate knowledge about forest succession, they attempt to identify the causal mechanisms of these dynamics. However, the large scales/long timeframes and variability of these processes may limit their inference space. For example, changes in tree species composition tend to occur over decades, limiting direct observation of such processes. Also, experts may remain conceptual (without explicit quantification) about the interrelationships among factors that influence forest succession and they may be uncertain about the importance of some factors and the generality of their conclusions.

Expert knowledge formed by individual experts working in a specific field, as described above, is often not formalized, and remains latent (Ford and Sterman 1998). Specifically, some critical aspects of that knowledge may not be explicit to anyone other than the individual experts who formulated it. These unknowns in a latent body of expert knowledge on forest succession make the knowledge necessarily uncertain because its traits are not known, and even the degree of uncertainty cannot be assessed until those traits are known and formalized.

Once the body of expert knowledge is made explicit, its traits can be used to assess the degree of uncertainty. Examples of such traits include, for example, the degree of confidence of individual experts in their knowledge, the degree of perceived complexity in knowledge by experts, and the variability in knowledge among experts. Confidence here refers to the strength of expert belief in their knowledge, as judged and expressed by them. Perceived complexity refers to the experts' view on the relative intricacies, variability, and unpredictability of a given succession process. By variability in knowledge among experts, we mean the level of disagreement among experts about the same knowledge. Specifically, expert knowledge may be deemed uncertain if either belief (degree of confidence) or evidence (estimate of variability of knowledge) for that knowledge is absent.

When a body of expert knowledge is made explicit, it can be tested as formal hypotheses by applying the scientific method with attempts to falsify those hypotheses. This helps to advance knowledge of succession in incremental steps, while identifying specific knowledge gaps as focal areas for research efforts.

Given that expert knowledge of forest succession is widely used in operational, tactical, and strategic planning of management of forests in Ontario and elsewhere (Sutherland et al. 2004, Pullin and Knight 2005), it is critical to reduce its uncertainty and increase its reliability. As well, the knowledge of forest succession may be improved by explicitly integrating expert knowledge with the published literature.

1.4. Goals and objectives

We developed a research study to elicit and test the expert knowledge of forest succession in boreal Ontario with the broad goal of assessing uncertainty and increasing reliability of that knowledge. To ensure that our findings are sound and reliable, we followed a rigorous and repeatable methodology for both eliciting expert knowledge and assessing its uncertainty. Our overall plan consists of three phases: (1) identify the uncertainty in expert knowledge, (2) formulate explicit hypotheses from expert knowledge and test those and (3) integrate expert knowledge and published literature.

This report focuses on the first phase of the study where expert knowledge is elicited and its uncertainty assessed (Figure 1). The specific objectives of this phase are to:

1. Elicit latent expert knowledge
2. Assess the uncertainty of expert knowledge expressed as an estimate of the degree of expert confidence and perceived complexity in knowledge (individual knowledge uncertainty)
3. Assess the uncertainty of expert knowledge expressed as variability among experts (collective knowledge uncertainty)
4. Assess the uncertainty of expert knowledge when expressed as a body of knowledge (composite knowledge uncertainty)

Subsequent documents will address the integration of published literature with expert knowledge, the formulation of explicit and falsifiable hypotheses, and testing those with empirical observations.

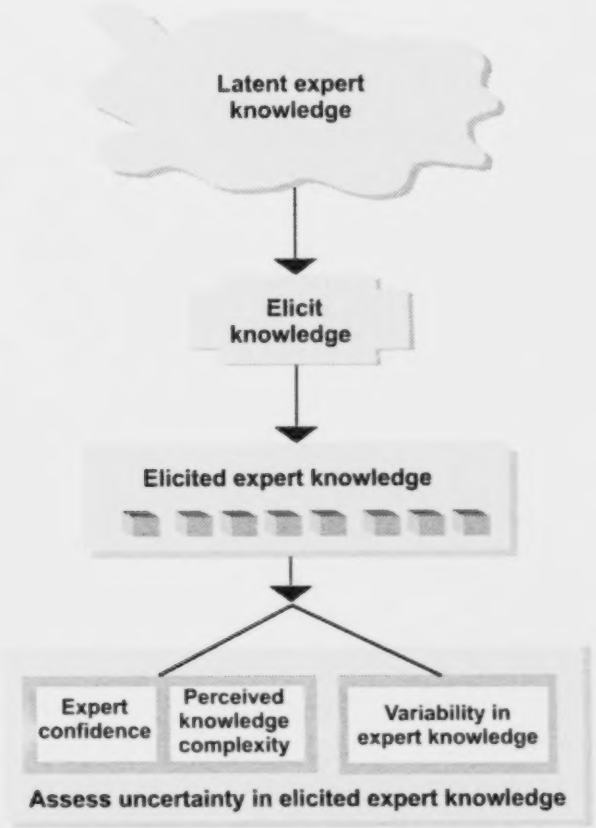

Figure 1. *Major steps involved in eliciting expert knowledge and assessing its uncertainty as applied to forest succession knowledge in Ontario.*

2. Methods

In this section, we detail the methods followed to address the stated study goals. First we provide an overview of what we mean by uncertainty in knowledge and its assessment as well as who we consider to be experts and possible approaches for eliciting their knowledge as context for readers who are unfamiliar with these topics. We also provide some background with respect to how forest succession knowledge is presently formulated and applied in Ontario. Second, we detail the methodological steps used to elicit knowledge from Ontario's forestry experts. Finally, we describe the information collected and the analytical methods used to quantify uncertainty in expert knowledge.

2.1. Background

2.1.1. Uncertainty in knowledge and its assessment

Uncertainty in knowledge is a vast and diverse field of study, where many different topics, goals, definitions, and assessment techniques are addressed. For the purpose of this study, we argue that when the knowledge is latent, i.e., when its traits are not known, it is necessarily uncertain, and only when the knowledge is made explicit, can its degree of uncertainty be assessed.

We urge readers to distinguish our goal of assessing uncertainty in knowledge from a frequent use of the term uncertainty assessment in literature. Our assessment of uncertainty does not address data and information uncertainty, where uncertainty is associated with aspatial data (Beechie et al. 2006), spatial data (e.g., Jordan et al. 2005), model parameter estimates (Hunter et al. 2000), model predictions (Parysow and Tazik 2002), and/or subsequent decision making (Pellikka et al. 2005).

Rather, we identified two main components of uncertainty of expert knowledge as relating to the major sources of uncertainty: (i) the uncertainty associated with *individual* experts, who together comprise the body of expert knowledge, and (ii) the *collective* uncertainty in expert knowledge when considered as an agglomeration of individual expert knowledge.

Individual expert uncertainty

We argue that the first component of uncertainty associated with *individual* experts has two dimensions: (i) the experts' degree of *confidence* about their knowledge, and (ii) the experts' perception of *complexity* of the forest succession processes that they abstracted to formulate that knowledge (Figure 2). When expert confidence is low and perceived complexity of knowledge is high, we deem uncertainty to be high. As expert confidence increases, and perceived complexity decreases, associated uncertainty becomes lower (Figure 2). However, in this assessment we consider expert confidence to weigh more than their perception of complexity. This is because if they are less confident in their knowledge, their perceptions also may not be accurate (even if knowledge is perceived to be simple). These two

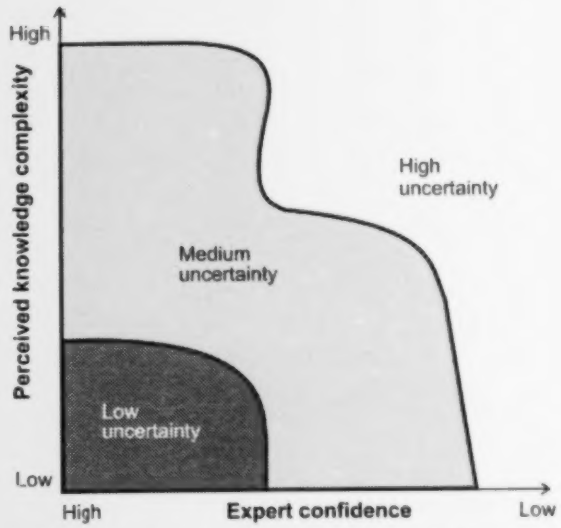

Figure 2. *A conceptual view of the two dimensions of uncertainty in knowledge of individual experts.*

dimensions of uncertainty are equivalent to *epistemic* and *aleatory* uncertainty as identified in the fields of natural resource management (Fogarty et al. 1996) and risk assessment (Bae et al. 2006, Li and Modarres 2005, Hora 1996, Parry 1996, Hoffman and Hammonds 1994). *Epistemic* uncertainty, which is also referred to as subjective uncertainty or reducible uncertainty, is caused by a lack of knowledge about the studied process and is equivalent to expert confidence in knowledge in our study. *Aleatory* uncertainty, which is also referred to as variability, irreducible uncertainty, or random uncertainty, arises from the inherent variability and unpredictability of a studied process and is equivalent to the perceived complexity of forest succession in our study.

Collective expert uncertainty

We assert that the second component of uncertainty, which is associated with the *collective* knowledge, is a result of the among-expert variability in knowledge of the same forest succession process. We deem that the among-expert variability is positively correlated with the degree of uncertainty associated with the body of expert knowledge. This aspect of uncertainty, concerning the entire body of knowledge arising from among-expert knowledge variability, has also been referred to as source conflict (Smithson 1999). Though the among-expert knowledge variability is commonly recognized in studies of the use of expert knowledge (e.g., Martin et al. 2005, Pellikka et al. 2005, Uusitalo et al. 2005), little work has occurred to quantify the extent of this type of uncertainty or to identify its causes. Instead, most work on among-expert variability is focused on aggregating conflicting expert knowledge (e.g., Maynard-Zhang and Lehmann 2003, Wallsten et al. 1997).

2.1.2. Experts and eliciting their knowledge

In general, experts in a given field of study are those who have considerable professional experience, and thus acquired knowledge, coupled with formal training (Ericsson et al. 1993). These experts are also generally recognized by their peers as sources of professional wisdom and their opinions are sought for solving professional problems (Hoffman et al. 1995). Descriptions of the development of expertise and the work of experts are found in literature from a variety of fields, for example technical professions (e.g., Allen et al. 2004, Wyman and Randel 1998), wildlife management (Yamada et al. 2003), and forest management (e.g. Morgan et al. 2001, MacMillan and Marshall 2006).

Various research methods are used for eliciting the knowledge that resides with such experts (e.g., Hoffman et al. 1995, Eriksson 1992). Huntington (2000), for example, distinguished among four different approaches in his examination and use of traditional ecological knowledge in science: (i) questionnaires, (ii) semi-directive interviews, (iii) analytical workshops, and (iv) collaborative field work. *Questionnaires* are useful if the required type of knowledge is known *a priori* and if a larger group of experts is consulted. This technique is most suitable for exploring simple aspects of expert knowledge. *Semi-directive interviews* are usually one-on-one conversations between a researcher and an expert. Topics covered and durations of interviews are determined by the expert. This technique is appropriate if the knowledge sought by the researchers is not specified *a priori*. *Analytical workshops* are appropriate for interpreting and analyzing knowledge considered to be established and discussing alternate views. This technique is suitable for eliciting knowledge from groups of experts. *Collaborative field work* requires extended interactions between the experts and the researcher and is especially suited when the knowledge elicited is mostly tacit and not easily formalized.

2.1.3. Ontario context

Study area

In Ontario, a hierarchy of ecogeographical units has been defined originally by Hills (1961) and revised many times since (e.g., Burger 1993). These ecogeographical units are meant to represent parts of Ontario's land base in which large-scale environmental factors behave similarly, leading to relatively uniform forest dynamics only subject to variation caused by history, species composition, and small- to intermediate-scale environmental factors.

The hierarchy of ecogeographical units as used in Ontario consists of ecozones, ecoregions, and ecodistricts, where ecozones are the spatially largest units. Ecozones are mainly based on the North-South gradient of temperature as determined by the transition zone of cold air masses from the sub-arctic and warm air masses from the South. Ecoregions are distinguished within ecozones and are mainly based on an East-West gradient of humidity (Burger 1993) as directed by the effect of humid air masses from the Atlantic. Ecoregions and ecodistricts progressively incorporate the effects of smaller-scale landforms, such as moderations of climate extremes by the Great Lakes, or prevalent surficial geological units, such as the clay deposits in the Great and Little Claybelt Regions (3E-1 and 3E-7).

Administrative regions of MNR that govern forest management in Ontario are approximate agglomerations of ecoregions. Boreal Ontario is administered by two regions, the Northeast and the Northwest Region. Presently, the Northeast Region encompasses ecoregions 0E, 1E, 2E, 3E, and 4E while the Northwest Region comprises ecoregions 2W, 3S, 3W, 4S, 4W, and 5S (Figure 3). These administrative regions play a significant role in the development and application of expert knowledge of forest succession: The definitions of forest cover composition and the derivation of forest cover transitions rules (as described below) are unique for each region.

We developed a research study to elicit and test the expert knowledge of forest succession in boreal Ontario (primarily ecoregions 3S, 4S, 3W, and 3E) with the broad goal of assessing uncertainty and increasing reliability of that knowledge.

Figure 3. *MNR administrative regions (shaded) and ecoregions (labelled polygons) in Ontario. In this report, we present results that primarily relate to expert knowledge uncertainty about forest succession in boreal ecoregions 3S, 4S, 3W, and 3E.*

Forest cover description

The MNR uses a system of forest classification to aggregate stands based on a combination of canopy tree species composition, environmental factors, and stand growth rate (= productivity). Based on these factors, a set of standard forest units (SFUs) are defined for use in strategic and operational planning. Specific definitions of SFUs are largely based on expert knowledge and differ between Northeast (Vasiliauskas et al. 2004) and Northwest (Ride et al. 2004) regions. The SFUs used for this study are listed in Table 1 (Northeast Region) and Table 2 (Northwest Region).

Table 1. *Description of MNR's Northeast Region standard successional forest units (adapted from John Parton, MNR, pers. comm. 2006) used in this study.*

Code	Name	Species composition*
PR1	Red pine dominated	Pr 70% + Po 20% + others
PW1	White pine dominated	Pw 40% + Bw 30% + Sw 10% + Sb 10%
PW2	Mixed red and white pine	Pr 30% + Pw 20% + Bw 10% + B 10% + Ce10%
LH1	Lowland hardwood	Lh 30% + Bw 30% + Po 10% + Sb 10% + Sw 10%
TH1	Tolerant hardwood	Bw 30% + Mh 20% + Uh 20% + Sw 10% + Lh 10%
SB1	Lowland black spruce	Sb 90%
PJ1	Jack pine dominated	Pj 80% + Sb 10%
LC1	Lowland coniferous	Sb 50% + Ce 20% + La 20%
PJ2	Mixed jack pine black spruce	Pj 60% + Sb 20% + Po 10%
SP1	Mixed black spruce jack pine	Sb 60% + Pj 20% + Bw 20% Po 10%
SF1	Mixed upland conifer	Sb 40% + Bf 10% + Bw 10% + Sw 10% + Ce 10%
PO1	Trembling aspen dominated	Po 60% + Bw 20% + Sb 10%
BW1	White birch dominated	Bw 50% + Po 20% + Sb 10%
MW1	Jack pine-trembling aspen mixedwood	Po 30% + Pj 30% + Bw 20% + Sb 20%
MW2	Boreal mixedwood	Bw 30% + Sb 30% + Po 20% + Sw 10% + Bf 10%

* Where Bf – balsam fir; Bw – white birch; Ce – cedar; La – larch; Lh – mix of black ash, balsam poplar, soft maple, and yellow birch; Mh – hard maple; Pj – jack pine; Po – trembling aspen; Pr – red pine; Pw – white pine; Sb – black spruce; Sw – white spruce

Table 2. *Description of MNR's Northwest Region standard forest units (adapted from Ride et al. 2004) used in this study.*

Code	Name	Species composition*
PrDom	Red pine dominated	Pr content ≥ 70%
PwDom	White pine dominated	Pw content ≥ 40%
PrwMx	Mixed red pine white pine	Pr + Pw content ≥ 40%
OthHd	Other hardwood	Mh + Uh + Lh ≥ 30%
HrDom	Hardwood dominated	Po + Bw + Mh + Uh + Lh ≥ 70%
SbLow	Lowland black spruce	(Sb + Ce + La ≥ 100% AND SC = 3 OR 4) OR (Sb + Ce + La = 100% AND Ce + La ≥ 10% AND SC = 1 OR 2)
PjDee	Jack pine dominated	Pj content ≥ 70%
OcLow	Lowland other conifer	(Ce + La ≥ 50% OR WG = Ce OR WG = La) AND Pr + Pw + Sw + Bw ≤ 10%
PjMx1	Jack pine mixed	Pr + Sb Pj + Sw + Bf ≥ 70% AND Bf ≤ 10% AND Po + Bw ≤ 20% AND Pj ≥ (Sb + Sw)
SbDee	Black spruce dominated	Sb content ≥ 70%
BfDom	Balsam fir dominated	Bf content ≥ 40% AND Bf + Sw + Sb + Pj ≥ 50%
PoDee	Trembling aspen dominated	Po content ≥ 70%
BwDom	White birch dominated	Bw content ≥ 70% AND Bw + Po content ≥ 70%
SbMx1	Black spruce mixed	Pr + Sb Pj + Sw + B ≥ 70% AND Bf ≤ 10% AND Po + Bw ≤ 20% AND (Sb + Sw) ≥ Pj
ConMx	Conifers mixed	Pw + Pr + Sb + Sw+ Bf + Pj + Ce + La ≥ 50%
HrdMx	Hardwood mixed	Po + Bw + Mh + Uh + Lh ≥ 70%

* Where Bf – balsam fir; Bw – white birch; Ce – cedar; La – larch; Lh – mix of black ash and balsam poplar; Mh – maple sp.; Pj – jack pine; Po – trembling aspen.; Pr – red pine; Pw – white pine; Sb – black spruce; Sw – white spruce; Uh – yellow birch, elm, oak, basswood; Con – conifer; Hrd – hardwood; Mx – mixed; SC – site class; WG – working group

Forest cover transition rules

Forest cover transition rules are attempts to formalize knowledge of forest succession processes in a quantitative and explicit manner, for use in predicting future states of forest stands. Every single transition rule describes only one step in the transitional dynamics that lead to the replacement of forest types by one another. For example, a single transition rule might describe the transition of a forest stand from forest type A to forest type *B*. Once the forest stand has made this transition, the previous rule no longer applies to this stand, since it is now in forest type *B*. Another transition rule now applies that might describe the transition of a forest stand from forest type *B* to forest type *C* or *D*. Though every single transition rule describes only one step in the transitional dynamics of forest stands, all transition rules together connect all forest types in a network of transition rules. The collective of all transition rules used is called a transition rule set.

Each rule in a forest cover transition rule set contains three types of explicit information: definitions (composition and age) of the states of forest stands (present and future), definition of the time period between transitions, and the probabilities with which the transition may occur.

A hypothetical example (Figure 4) of forest cover transition for two distinct types of succession is:

(i) Post-fire establishment: A stand of forest type A replaces itself with probability f_{AA}; or is replaced by a stand of forest type B with probability f_{AB}, or by a stand of forest type C with probability f_{AC}.

(ii) Natural succession through time: A stand of forest type A is replaced by a stand of forest type D with probability s_{AD} after u years, or replaced by a stand of forest type E with probability s_{AE} after v years.

For forest management purposes in Ontario, the forest cover transition rules used in forest management planning are based on SFUs, and differ between Northeast (Vasiliauskas et al. 2004) and Northwest (Ride et al. 2004) regions. The knowledge base from which these forest stand transition rules are derived for the various spatial levels is mainly expert knowledge, unpublished observations, and reports. Forest stand transition rules for a few forest cover types, such as black spruce-dominated stands, have been specified at the level of site condition to differentiate, for example, between dry upland and wet lowland sites (e.g., Ride et al. 2004). However, for most forest cover types, forest stand transition rules are not differentiated by site conditions, especially not for subtle differences, such as mesic versus wet soil moisture regime or mesotrophic versus rich soil nutrient regime. Though it is generally acknowledged that such variations in site conditions play a role in determining successional dynamics, they have not yet been sufficiently quantified to generate evidence-based transition rules.

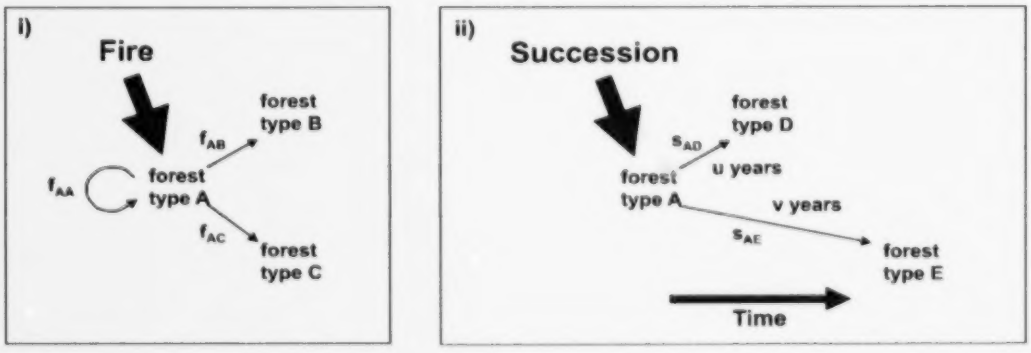

Figure 4. *An illustration of stand-level forest succession knowledge as explicit, quantitative rules describing forest cover transitions: (i) immediate forest cover establishment after fire – where f_{AA}, f_{AB} and f_{AC} denote probabilities of transitions, (ii) replacement of a forest stand due to succession over time – where S_{AD} and S_{AE} denote probabilities of transition.*

Final forest cover transition rules are a result of the consensus knowledge of regional forestry experts and specified mostly at ecoregion, but sometimes at ecodistrict resolution. Although these rules have been generalized and published as 'suggested rule sets', they are continually revised during local applications at the forest management unit levels to reflect knowledge of local conditions.

2.2. Eliciting knowledge from Ontario forestry experts

In this study, the steps involved in eliciting knowledge included selecting and grouping experts, selecting appropriate approaches, and implementing those approaches. Planning these steps involved discussions with Ontario's policymakers and regional planners and formal review of a study proposal. The planning phase occurred over eleven months (May 2005-March 2006) and involved ongoing consultation with regional experts, examination of possible approaches, proposal development and review, and a trial workshop (Figure 5). The implementation phase of knowledge elicitation occurred over two months (mid-April to mid-June 2006) and involved conducting the knowledge elicitation workshops with regional experts. Details of the steps and timing for the knowledge elicitation process are provided in Appendix I.

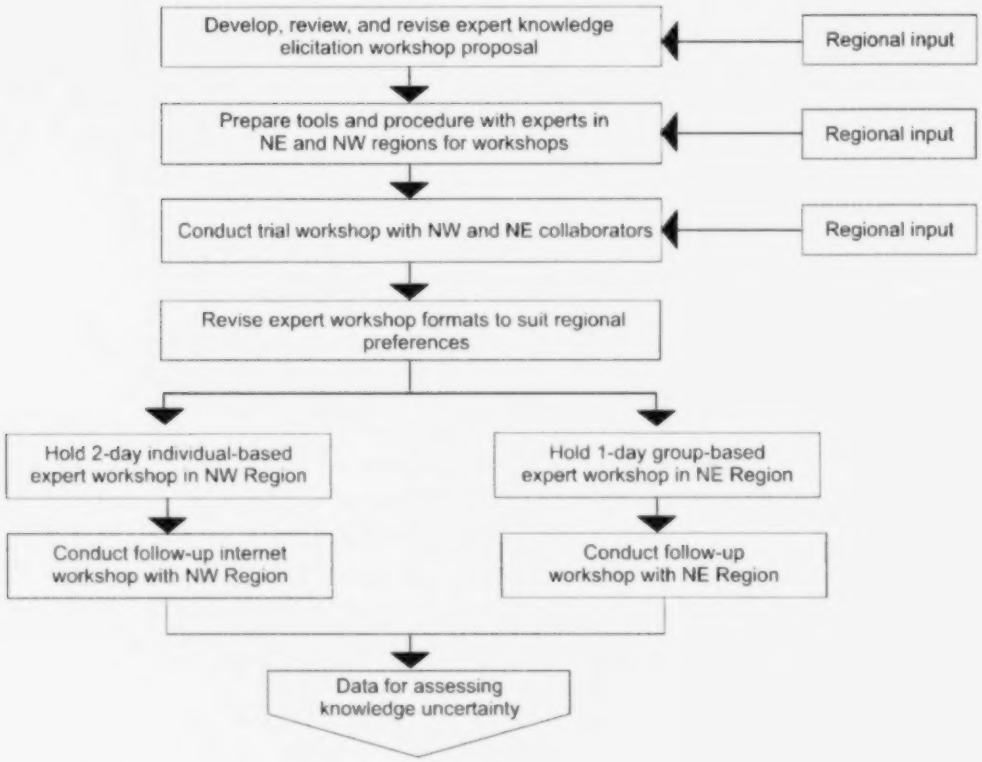
Develop, review, and revise expert knowledge elicitation workshop proposal
Regional input
Prepare tools and procedure with experts in NE and NW regions for workshops
Regional input
Conduct trial workshop with NW and NE collaborators
Regional input
Revise expert workshop formats to suit regional preferences
Hold 2-day individual-based expert workshop in NW Region
Hold 1-day group-based expert workshop in NE Region
Conduct follow-up internet workshop with NW Region
Conduct follow-up workshop with NE Region
Data for assessing knowledge uncertainty

Figure 5. *Process of developing and conducting knowledge elicitation workshops in MNR's Northeast (NE) and Northwest (NW) regions in 2006.*

2.2.1. Characteristics of participants

The Ontario forestry experts selected to participate in this study included foresters, forest ecologists, and forest management planning analysts, all with extensive practical experience in forestry, much of it related specifically to forest succession. These experts are also recognized by their peers as specialists in various facets of forest management in boreal Ontario. Their breadth of expertise is reflected in their years of experience, which ranged from 10 to 35. In addition, selected experts voluntarily expressed willingness to participate and were interested in the outcome of the proposed knowledge elicitation and analysis.

2.2.2. Knowledge elicitation approach

As mentioned above, expert knowledge on forest succession in Ontario has been captured to some extent as suggested forest cover transition rule sets for each of the administrative regions: Vasiliauskas et al. (2004) for Northeast Region and Ride et al. (2004) for Northwest Region. Therefore, we chose the analytical workshop approach where we could use the information in those documents as a guide to facilitate the exploration and elicitation of expert knowledge on forest succession. Furthermore, we combined some elements of the questionnaire approach (to guide and focus discussions) with the analytical workshop approach (to allow direct contact between researchers and experts and the opportunity to explore and discuss beyond *a priori* questions). An description of the protocol used to guide experts during the workshops is provided in Appendix II.

During the guided workshops, experts were expected to review regional forest cover transition rule sets for post-fire forest cover establishment and subsequent natural succession. This separation of rule sets distinguishes between two major stages of forest succession: immediate response to disturbances and more gradual, long-term replacement of forest cover. The workshops were planned as focused working sessions, guided by workshop leaders (a regional expert), during which the latent knowledge of individual experts was to be captured in explicit, quantitative terms. The intent was not to merge expert knowledge as a group consensus, but to capture and retain knowledge of individual experts. The workshop format was expected to allow experts to exchange information, share experiences, and explore similarities and differences between observed forest cover transitions and stated transition rules but still allow the capture of individual expert knowledge using the structured questionnaire.

To account for differences in ecological conditions in boreal forests of Ontario and to accommodate differences in forest management approaches, separate workshops were held for the Northeast and Northwest administrative regions.

2.2.3. Knowledge elicitation process

Prior to the regional expert workshops, a trial workshop was held to examine the feasibility of the proposed approach and adapt it as necessary. The workshop leaders selected from each region participated in this session, in which the planned questionnaire approach was tested. Subsequently, the proposed approach was customized for each administrative region (Figure 5).

As indicated previously, the ecological conditions and their use in formulating regional forest cover transition rules differ between the regions. Different combinations of ecogeographical units, site conditions, and forest units in each region resulted in 330 possible transition rules each for post-fire establishment and natural succession in Northeast Region and 3872 in Northwest Region (Figure 6).

Because we wanted to conduct the elicitation process within a time frame sufficiently short to encourage maximum participation of regional experts, we expected that less than 150 transition rules could be examined during a workshop, thus making it impossible to elicit expert knowledge for all combinations during this study. Therefore, experts in each region were asked to prioritize the forest cover transition rules for their respective regions prior to the workshops. In the Northwest, experts selected the rule sets that they thought were of highest economic importance and about which they knew the least. In the Northeast, rule sets were selected based on the

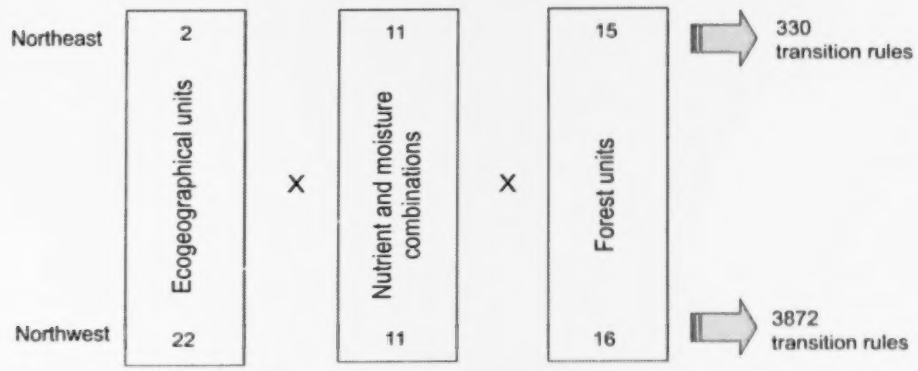

Figure 6. *Combinations of ecogeographical units, site conditions, and forest units that result in multiple transitions rules in each administrative region for natural succession and post-fire establishment.*

likely frequency of occurrence on the landscape, using an unpublished regional succession database as a guide. The priority lists of forest cover transition rule sets generated by the experts to be evaluated at the workshop are detailed in Appendix III for the Northeast Region and Appendix IV for the Northwest Region.

In addition to the nature and the number of rules to be examined, the format of workshops also differed between regions. Based on the preference of the experts, the approach in the Northeast region was changed from the planned individual-based approach to a group consensus approach.

2.2.4. Knowledge elicitation in Northeast Region

Nine experts were invited to the Northeast workshop, but only seven could attend. They collectively represented 145 years of practical forestry experience, mostly in that region.

Experts were asked to review the available expert knowledge formulated as suggested forest cover transition rules for the Northeast Region for post-fire establishment and natural succession for all combinations of forest cover types with site conditions both in the Claybelt, and outside. A group concensus approach was used in this region resulting in a single set of forest cover transition rules for the group rather than a set for each of the experts.

As part of the review of a specific forest cover transition rule, the expert group had to decide whether they agreed with:

(i) the identity of the standard forest units that were linked by the transition rule,

(ii) the probabilities specified for the transitions, and

(iii) for successional transitions, the timing of the transitions.

If the group agreed with a specific forest cover transition rule, this rule became part of the group's final transition rule set. If they did not agree with the forest cover transition rule, they were invited to formulate a new transition rule based on their knowledge, which then became part of the group's transition rule set (Figure 7).

An one-day in-person guided workshop with six experts was followed by an additional one-day meeting, involving only three of the experts who participated in the first session, during which most of the prioritized forest cover transitions rule sets were reviewed by attending experts. The three experts finished reviewing the rule sets on their own.

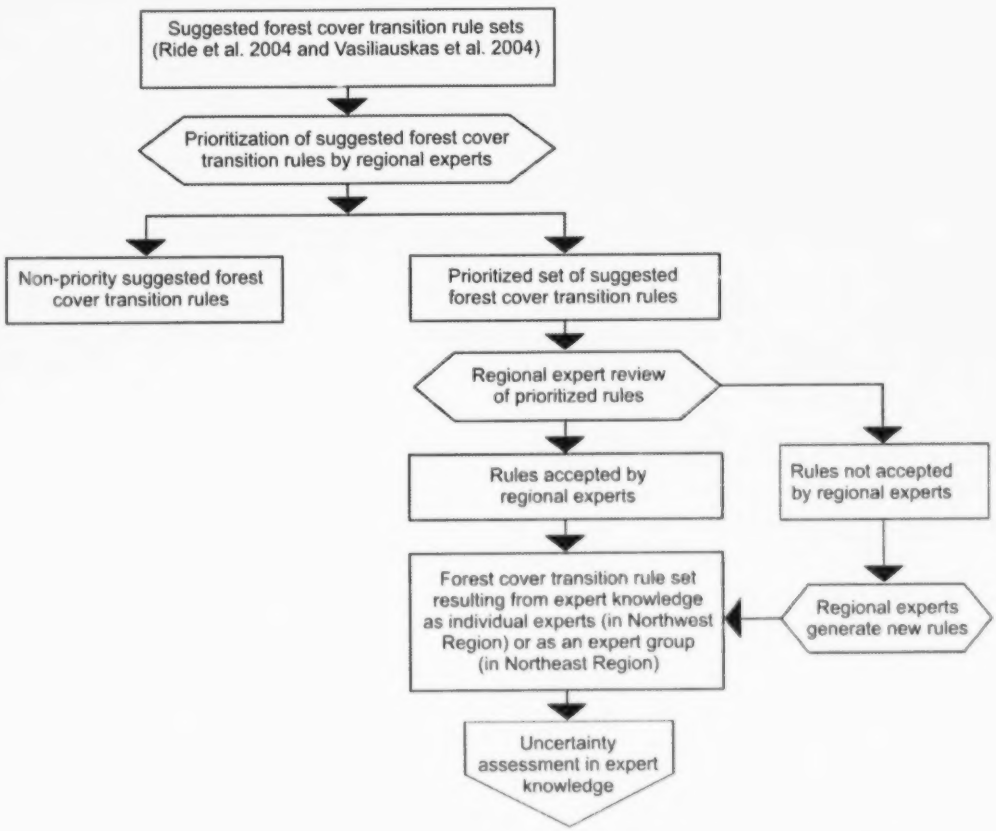
Suggested forest cover transition rule sets (Ride et al. 2004 and Vasiliauskas et al. 2004)
Prioritization of suggested forest cover transition rules by regional experts
Non-priority suggested forest cover transition rules
Prioritized set of suggested forest cover transition rules
Regional expert review of prioritized rules
Rules accepted by regional experts
Rules not accepted by regional experts
Forest cover transition rule set resulting from expert knowledge as individual experts (in Northwest Region) or as an expert group (in Northeast Region)
Regional experts generate new rules
Uncertainty assessment in expert knowledge

Figure 7. *Process used for review of forest cover transition rules by regional experts during the knowledge elicitation process.*

2.2.5. Knowledge elicitation in Northwest Region

Nine experts were invited to the Northwest workshop, but only six could attend. They collectively represented 164 years of practical forestry experience, mostly in that region.

The process used was identical to that used in the Northeast (Figure 5), except that each individual expert was asked to review the prioritized forest cover transition rules on a rule-by-rule basis for post-fire forest cover establishment and natural succession. If an expert agreed with a specific forest cover transition rule, this rule became part of the individual's transition rule set. If they did not agree with the forest cover transition rule, they were invited to formulate a new rule based on their individual knowledge, and this then became part of their individual transition rule set.

Over the course of a two-day in-person guided workshop and a one-day follow-up guided netmeeting, about two thirds of the prioritized forest cover transitions rule sets were reviewed by the regional experts.

2.3. Assessing uncertainty in expert knowledge

As mentioned above, we consider the overall uncertainty in expert knowledge to be composed of two major sources: individual expert knowledge uncertainty and collective expert knowledge uncertainty. Individual expert knowledge uncertainty is assessed by quantifying the expert's degree of confidence in their knowledge and the degree of perceived complexity in forest succession. Collective expert knowledge uncertainty is quantified by the extent of the variability among experts in their knowledge. The analytical methods for individual expert knowledge uncertainty, i.e., assessing confidence in expert knowledge and perceived complexity of the forest succession process, were similar for the two groupings of experts (Northeast and Northwest regions). The assessment of collective expert knowledge uncertainty by analyzing among-expert variability in their knowledge was possible only for Northwest Region. The group format of knowledge elicitation adopted by Northeast Region did not allow among-expert variability to be quantified and hence collective expert knowledge uncertainty and composite knowledge uncertainty could not be assessed. In addition to the uncertainty assessment, we also examine the relationship of expert knowledge uncertainty with associated variables, such as forest cover types and site conditions that may help to explain variability.

2.3.1. Assessing individual knowledge uncertainty in the Northeast and Northwest regions

Quantifying expert confidence in knowledge

Experts were presented with the prioritized list of suggested forest cover transition rules for review during the workshops. They were asked to state their *confidence* in each rule as a categorical ranking: low (*Lc*), medium (*Mc*), and high (*Hc*). These rankings were primarily based on experts' assessment of the nature of the evidence (quality and extent) that supports the rule in question. At one extreme, experts would assign a high degree of confidence for rules that they believe are predicated on rigorous and ample evidence. At the other extreme, experts would assign a low degree of confidence to rules that they believe are predicated on vague and limited evidence.

Quantifying perceived complexity in expert knowledge

Following the review of each prioritized forest cover transition rule, experts were asked to rank their perception of *complexity* of natural forest succession associated with each rule into categories of low (*Lx*), medium (*Mx*), and high (*Hx*). At one extreme, experts would assign a high ranking to forest succession processes they deem complex in terms of spatio-temporal variation in causal factors, inherent stochasticity, and number of possible forest cover states in outcomes. At the other extreme, experts would assign a low ranking to forest succession processes they deem simple relative to abovementioned factors.

In the Northeast Region, confidence in each rule was assessed by the experts as a group. In the Northwest Region, expert confidence in each rule was assessed by each individual expert.

Quantifying individual knowledge uncertainty

The logic of analysis followed the approach described earlier (see Figure 2, where we considered expert confidence and perceived complexity as the two dimensions of uncertainty associated with individual expert knowledge) and the ranks of expert confidence and perceived complexity for each transition rule were used to define the degree of uncertainty. Low uncertainty was associated with high confidence and low complexity, and high uncertainty was associated with low confidence and high complexity. In surveys, respondents often select medium when not sure (e.g., Christenfeld 1995, Shaw et al. 2000, Attila and Bar-Hillel 2003). Therefore, we adopted a conservative view in assigning weights to rankings: instead of assigning weights of 1, 0, and -1 to high, medium, and low confidence (and low, medium, and high complexity), respectively, we biased the medium responses negatively. This is analogous to controlling type I error to prevent a false positive conclusion. Furthermore, we weighted the confidence dimension more than the complexity dimension, because lack of confidence in knowledge may indicate a higher uncertainty than perceived complexity. Specifically, (a) we doubled the weight of expert

confidence to account for its higher value in the uncertainty assessment (2, -1, -4 for confidence and 1, -0.5, and -2 for complexity); and (b) when experts ranked confidence and/or complexity as medium, we weighted those towards low for confidence (by -1) and high for complexity (by -0.5).

The sums of rank-weights from the two dimensions generated a matrix of uncertainty as illustrated in Figure 8. We categorized the degree of uncertainty as high (*H*) when the sum < 0; medium (*M*) when the sum = 0, and low (*L*) when the sum > 0.

2.3.2. Assessing collective knowledge uncertainty in the Northwest Region

Collective expert knowledge uncertainty is directly estimated by the among-expert variability. This was quantified by the degree of agreement among experts on pathway structures in forest cover transition rules. For this exercise, we defined the pathway structure of a transitional rule as the specific states a given forest cover could attain in one time step. An agreement occurred when at least two experts defined the same pathway structure for a given transition rule. If two experts asserted different future states of forest cover for a transition rule, this implied a disagreement. Differences in expert's assessment of the probabilities of occurrence of these states were not considered disagreements (Figure 9).

The higher the number of experts who disagreed about the structure of a transitional pathway in a given rule, the higher the variability in knowledge among experts for that particular rule. We assigned different categories of variability based on expert responses: very high when all experts disagreed with one another, high when more experts disagreed than agreed, low when more experts agreed than disagreed, and very low when all experts agreed. This among-expert variability corresponds directly with the degree of collective expert knowledge uncertainty (i.e., very high variability = very high collective uncertainty, high variability = high collective uncertainty, low variability = low collective uncertainty, and very low variability = very low collective uncertainty).

Perceived knowledge complexity (rank - weights)	Expert confidence (rank - weights)		
	Hc (2)	*Mc (-1)*	*Lc (-4)*
Lx (1)	L (3)	M (0)	H (-3)
Mx (-0.5)	L (1.5)	H (-1.5)	H (-4.5)
Hx (-2)	M (0)	H (-3)	H (-6)

Figure 8. *Individual expert knowledge uncertainty assessed by degree of expert confidence (*Hc=*high;* Mc=*medium;* Lc=*low) and perceived complexity of forest succession knowledge (*Hx=*high;* Mx=*medium;* Lx=*low). Italic numbers in parentheses indicate the rank-weights of expert confidence and perceived knowledge complexity. The remaining numbers in parentheses indicate the row-column sum. Degree of uncertainty is high (H) when the sum < 0; medium (M) when the sum = 0, and low (L) when the sum > 0.*

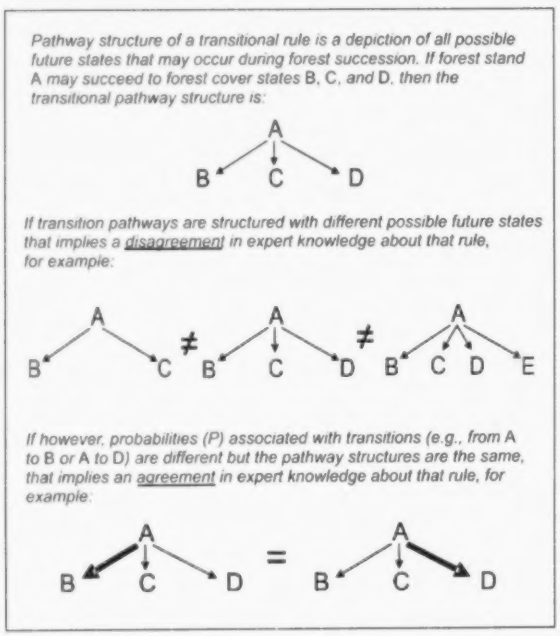
Pathway structure of a transitional rule is a depiction of all possible future states that may occur during forest succession. If forest stand A may succeed to forest cover states B, C, and D, then the transitional pathway structure is:
A
B C D
If transition pathways are structured with different possible future states that implies a disagreement in expert knowledge about that rule, for example:
A
B C
≠
A
B C D
≠
A
B C D E
If however, probabilities (P) associated with transitions (e.g., from A to B or A to D) are different but the pathway structures are the same, that implies an agreement in expert knowledge about that rule, for example:
A
B C D
=
A
B C D

Figure 9. *An illustration of a hypothetical pathway structure of a transition rule showing when differences in expert knowledge are considered disagreement or agreement.*

2.3.3. Assessing composite knowledge uncertainty in the Northwest Region

Similar to assessing individual expert knowledge uncertainty as a function of two lower level factors (confidence and complexity), we assessed composite expert knowledge uncertainty as the composite of individual expert knowledge uncertainty and collective expert knowledge uncertainty. We assessed degree of composite expert knowledge uncertainty for each prioritized forest succession rule following the general approach shown in Figure 10.

When the weights were assigned to the two dimensions of uncertainty, we doubled the weight of high individual expert knowledge uncertainty (to -2 from -1) to account for its wide range of possible numerical values (see Figure 8). The resulting rank-weight matrix of composite uncertainty is illustrated in Figure 11, where the degree of composite uncertainty is high (*H*) when the sum < 0; medium (*M*) when the sum = 0, and low (*L*) when the sum > 0.

2.4. Data analyses

2.4.1. Data aggregation

During the knowledge elicitation process, experts addressed their knowledge at a higher resolution, finer than the level of the individual transition rule set: for post-fire transition rules, experts expressed their confidence in and perceived complexity of knowledge for each individual connection between forest units within the larger transition rule and for natural succession transition rules, they expressed their knowledge for each individual connection between forest units, as well for individual time steps within a connection. Therefore, we had to aggregate the gathered raw data to rescale the information to the transition rule level. For post-fire establishment rules, we aggregated the data by determining the median level of confidence and complexity of all sub-rules within one transition rule. Since we assumed that experts were more likely to select medium confidence and complexity than high or low complexity, median values that fell between two levels (low and medium, or medium and high) were assigned the extremes (low or high). For succession rules, we first aggregated the confidence and complexity values over all time steps for each connection between forest units. Afterwards we followed the same approach described above to aggregate sub-rules within rules.

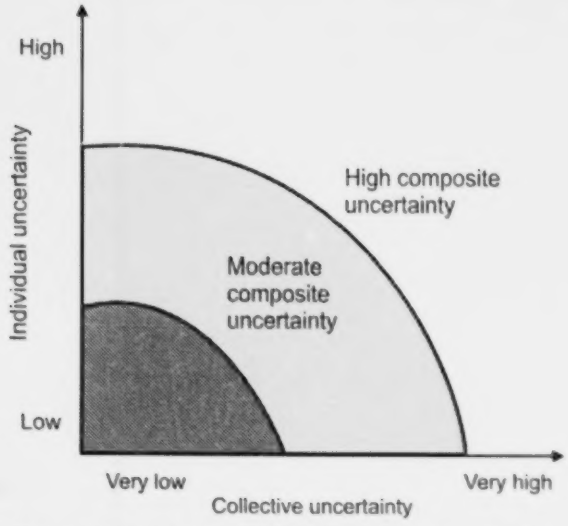

Figure 10. *An abstraction of the relationship of individual and collective expert knowledge uncertainty resulting in composite uncertainty.*

Collective-expert knowledge uncertainty (rank-weights)

Individual expert-knowledge uncertainty (rank-weights)	$VL_{(+2)}$	$L_{(+1)}$	$H_{(-1)}$	$VH_{(-2)}$
$L_{(+1)}$	$L_{(3)}$	$L_{(2)}$	$M_{(0)}$	$H_{(-1)}$
$M_{(0)}$	$L_{(2)}$	$L_{(1)}$	$H_{(-1)}$	$H_{(-2)}$
$H_{(-2)}$	$M_{(0)}$	$H_{(-1)}$	$H_{(-3)}$	$H_{(-4)}$

Figure 11. *Composite expert knowledge uncertainty assessed by collective expert knowledge uncertainty and individual expert knowledge uncertainty (H=high; M=medium; L=low; VL=very low). Italic numbers in parentheses indicate the rank-weights associated with collective expert knowledge uncertainty and individual expert knowledge uncertainty. The remaining numbers in parentheses indicate the row-column sum. Degree of composite uncertainty is high (H) when the sum < 0; medium (M) when the sum = 0, and low (L) when the sum > 0.*

2.4.2. Statistical tests

Rationale

The choice of techniques for the statistical data analysis was determined primarily by the nature of our data set. Data collected for this study are characterized by:

(i) Small sample size due to logistical limitations (for example, ready availability of experts and the length of knowledge elicitation process)

(ii) Categorical data: since the resolution of the observed variables is limited, data points were collected in classes. While the independent variables may be treated as nominal variables, the dependent variables are of ordinal scale.

(iii) Non-random sample: Since the reviewed transition rules were pre-selected and prioritized by experts, these may not constitute a random sample of all transition rules.

Given these characteristics of our data set, statistical tests that require large samples (e.g., log linear regression, logistical regression), interval or ratio-scale data (e.g., standard deviation, linear regression), or randomness in samples could not be used. We therefore applied measures of central tendency and measures of association, which are compatible with the nature of our data set.

Measures of central tendency

Measures of central tendency (MCT) indicate the overall position of a distribution. In our case, a MCT is used to indicate the general trend of all recorded values (confidence in knowledge, perceived complexity of knowledge, collective uncertainty) as well as estimated values (individual and composite uncertainty of knowledge). The most useful MCT depends on the scale of the measurement as well as the spread and the shape of the distribution of the variable.

Our data (complexity, confidence, and uncertainty) are ordinal variables, and the appropriate MCTs for these are mode and median (see Table 3).

Table 3. *Applicability of common measures of central tendency given the scale of measurement of the data collected for this study (Y = applicable and N = not applicable).*

Scale of measurement	Measure of central tendency		
	Mode	Median	Mean
Nominal	Y	N	N
Ordinal	Y	Y	N
Interval/ratio	Y	Y	Y

The median contains the information about the ranking of the individual observations and therefore is more informative than the mode. In our analyses, we used median as the principle measure of central tendency. The mean was used only to determine the average of the ranked observations (i.e., not the actual mean response, which may fall between two response levels).

Measures of spread

Measures of spread (MS), together with higher moments, indicate the shape of a distribution. In our case, we are using MS to indicate variability in confidence, complexity, and uncertainty. Which MS is most useful depends on the scale of the measurement of the variable as well as its spread and the shape of the distribution.

The shape of the distribution of random, real-valued variables is often indicated by the use of the higher moments-based skewness and kurtosis. Because the dependent variables in this study are categorical variables with ordinal ranks, it is not appropriate to use measures of skewness and kurtosis based on higher moments to indicate the spread of the distributions. It is possible to investigate the shape of the distribution for ordinal variables with measures specifically appropriate for such variables. While many such MS are available (see Table 4), some are not suitable for our data. For example, common measures such as standard deviation may not be appropriate because our dependent variables are ordinal. Also, because of the small number of classes we are using (n = 3), the range and inter-quartile range do not give much information.

In this study, for the MS we make use of the *measure of ordinal concentration* (d^2, Blair and Lacy 2000) that is defined as:

$$d^2 = \sum_{i=1}^{k-1}\left(F_i - \frac{1}{2}\right)^2 \; with \; F_i = \sum_{i=1}^{i} p_i$$

where, k is the number of classes of observations, F_i is the cumulative proportion of class i, and p_i is the proportion of class i. Different from MS for nominal data, as for example shown in Table 4, this measure does use the information contained in the ranking of the classes. The measure of ordinal concentration is sensitive to the number of classes (k) and therefore comparing its value between distributions using different numbers of classes is not advised. Blair and Lacy (2000) also developed a normed or standardized derivative of this statistic, termed *normed measure of ordinal concentration* (I^2). Norming the measure of ordinal concentration, in relation to the maximum ordinal concentration, scales its values from 0 to 1 as defined below.

Table 4. *Applicability of some common measures of spread given the scale of measurement of the data collected for this study (Y = applicable and N = not applicable).*

Scale of measurement	Measure of spread			
	Index of dispersion*	Range	Inter-quartile range	Standard deviation
Nominal	Y	N	N	N
Ordinal	Y/N	Y/N	Y	N
Interval/ratio	N	Y	Y	Y

* refers specifically to the index of dispersion (ID) of Loether and McTavish (1974)

$$I^2 = \frac{d^2}{d^2_{max}} \; with \; d^2_{max} = \frac{k-1}{4}$$

Here we illustrate the use of the normed measure of ordinal concentration: It approaches 1 when all observations fall in any one of the k classes of the categorically ranked variable, and approaches 0 when exactly half of the observations fall in each of the two most extremely ranked classes. Examples of the behaviour of the normed measure of ordinal concentration for 150 observations categorized in three classes are shown in Figure 12.

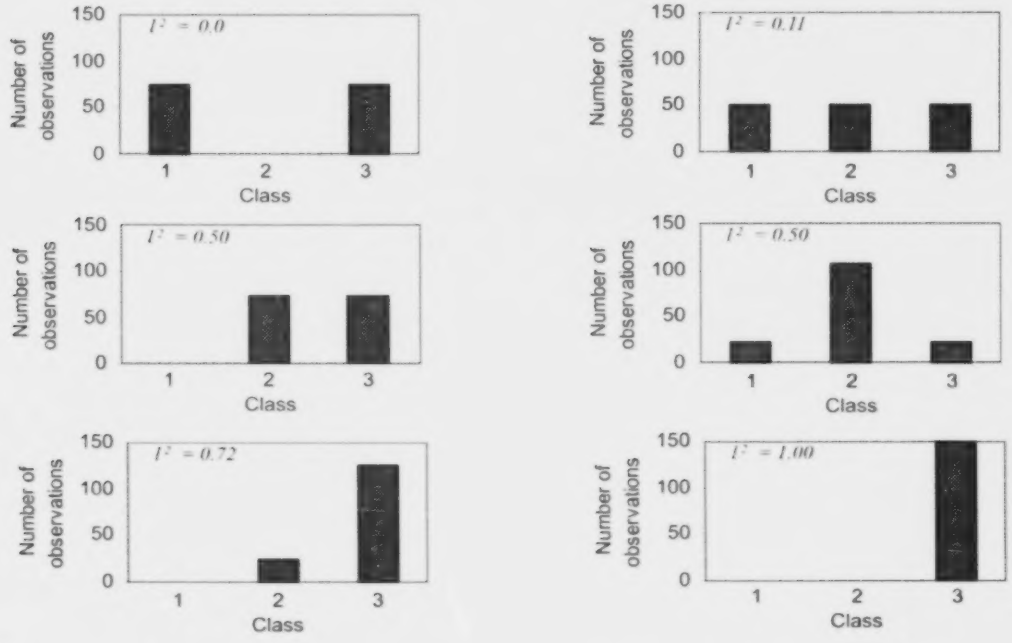

Figure 12. *Examples of the value of the normed ordinal concentration (I^2) in relation to the distribution of 150 observations of an ordinal variable over three classes.*

While extreme values of the normed measure of ordinal concentration are relatively easy to interpret, values around 0.5 are not. As illustrated by the examples in Figure 12, values close to 0.5 can arise from an even distribution of observations over only two classes or from an even distribution of observations over the two extreme classes bordering one centre class. However, measures such as the range, median, and mean can help to distinguish between these cases. A direct statistical test of significance of the normed measure of ordinal concentration is not yet developed.

Statistical test of association

The characteristics of our data set make the use of advanced statistical techniques infeasible. In particular, because our sample size is small, many combinations of dependent and independent variables have few or no observations. This would result in an increased Type II error when applied to a multi-factorial design.

Instead, we chose measures of association applied to 2-way contingency tables. Measures of association can be applied to nominal or ordinal variables, do not depend on the condition of a random sample, and do not necessarily require large data sets if only two factors are analyzed in a contingency table. Various measures of association are available that differ in many respects, for example, whether they apply to nominal or ordinal data, whether they are asymmetric or symmetric (i.e., whether they identify a dependent variable or not), and how easily they can be interpreted. A review of a number of commonly used measures of association, including their similarities and differences, can be found in Garson (2006).

In this study, we used Theil's uncertainty coefficient (UC, Theil 1972 in SAS 2000)[1] as measure of association. Theil's coefficient (*T*) for an independent variable (*I*) given a dependent variable (*D*) is a function of the heterogeneity in the information (*H*):

$$T(I \mid D) = \frac{H(X) + H(Y) - H(XY)}{H(Y)}$$

where $H(X)$, $H(Y)$, and $H(XY)$ indicate the heterogeneity of information in the rows, columns, and cells in a contingency table. The value of Theil's coefficient ranges from 0 to 1, where 0 indicates independence of the two variables, and 1 indicates a perfect relationship between the two variables (for more details on Theil's coefficient see Appendix V).

We determined the strength of association between the dependent variables, expert confidence in knowledge, perceived complexity of knowledge, and collective expert uncertainty, with a set of independent variables that are characteristics of transition rules, such as forest unit classification, dominant leaf type group[2], soil moisture regime level, and soil nutrient regime level.

Since we are determining the significance of the strength of association for a number of 2-way contingency tables of dependent and independent variables, we are increasing the probability of making a Type I error. To decrease the probability of this error, we applied the sequential Bonferroni correction (Rice 1989) to the group of tests for each dependent variable, to lower the α-value at which a result is considered statistically significant. Since this correction is considered conservative by some, it is commonplace to report results with uncorrected P-values as well.

A summary of the analytical approaches used in assessing the components of uncertainty of expert knowledge in forest succession in this study is provided in Figure 13.

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[1] Theil's uncertainty coefficient is not a measure of uncertainty in knowledge, but a statistical measure of association. To avoid confusion, henceforth we call it Theil's coefficient.

[2] Leaf type groups are coniferous, hardwood, and mixedwood

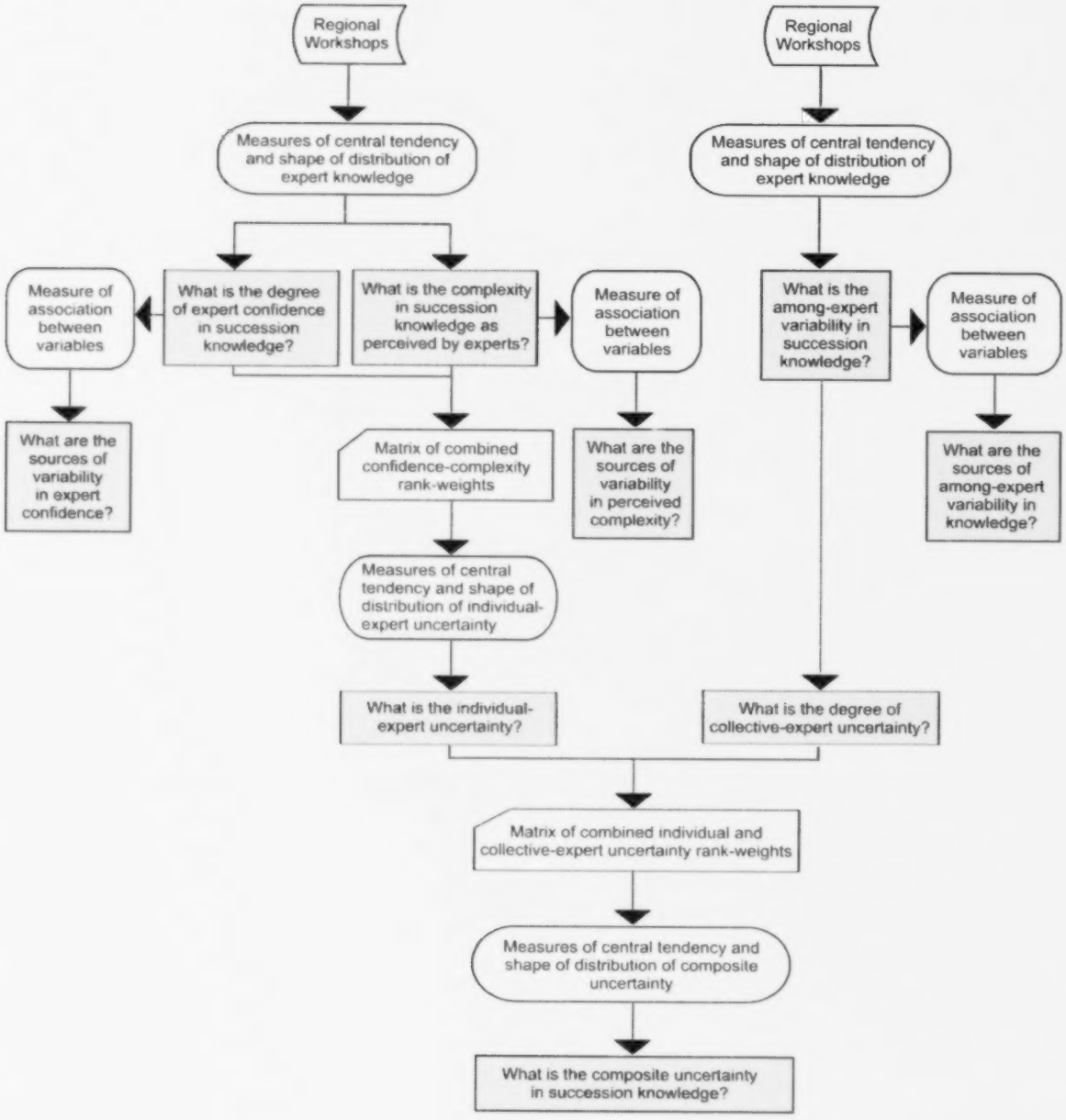
Regional Workshops
Measures of central tendency and shape of distribution of expert knowledge
Measure of association between variables
What are the sources of variability in expert confidence?
What is the degree of expert confidence in succession knowledge?
What is the complexity in succession knowledge as perceived by experts?
Measure of association between variables
What are the sources of variability in perceived complexity?
Matrix of combined confidence-complexity rank-weights
Measures of central tendency and shape of distribution of individual-expert uncertainty
What is the individual-expert uncertainty?
Regional Workshops
Measures of central tendency and shape of distribution of expert knowledge
What is the among-expert variability in succession knowledge?
Measure of association between variables
What are the sources of among-expert variability in knowledge?
What is the degree of collective-expert uncertainty?
Matrix of combined individual and collective-expert uncertainty rank-weights
Measures of central tendency and shape of distribution of composite uncertainty
What is the composite uncertainty in succession knowledge?

***Figure 13**. An overview of the analytical approaches used in assessing uncertainty of expert knowledge of forest succession and its components in this study.*

3. Results

As outlined in the methods, we used elicited expert knowledge to assess two dimensions of uncertainty (expert confidence in their knowledge and perceived complexity of forest succession) to determine expert uncertainty. Since the knowledge elicitation and subsequent data analyses were conducted separately in the two administrative regions, the results are also presented and discussed independently. Knowledge elicited from experts and an assessment of their confidence, perceived complexity, and uncertainty in that knowledge, as an expert group in Northeast Region, is presented first. This is followed by the results of knowledge elicited from individual experts and analysis of their confidence, perceived complexity, and among-expert variability, as well as assessment of individual, collective, and composite uncertainties in knowledge in Northwest Region. Among-expert variability is a direct estimate of collective uncertainty. Within each region, results are presented and discussed separately for post-fire establishment and natural succession. In each section, a data summary is presented first, followed by analyses of components of uncertainty, their association with characteristics of transition rules, and an assessment of uncertainty. Finally, a summary of overall results provides a view of the generalities in knowledge uncertainty across the regions and succession types. Figure 14 provides a guide to the results section.

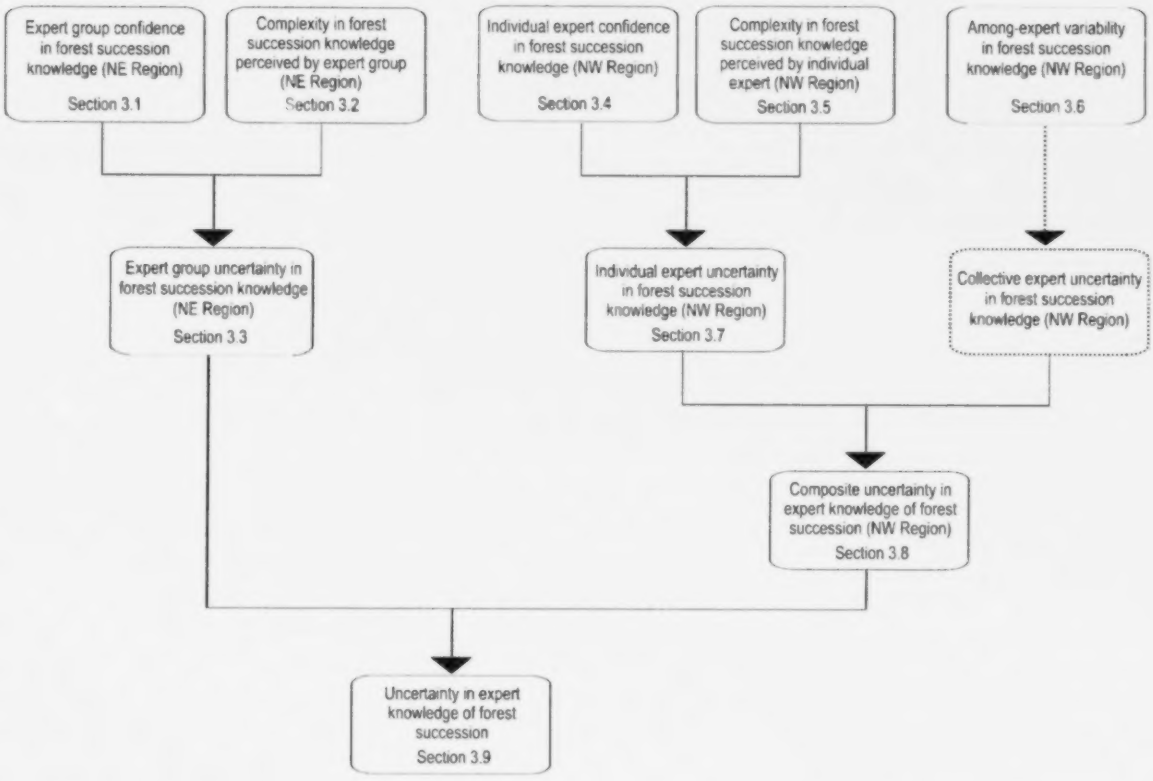
Expert group confidence in forest succession knowledge (NE Region)
Section 3.1
Complexity in forest succession knowledge perceived by expert group (NE Region)
Section 3.2
Individual expert confidence in forest succession knowledge (NW Region)
Section 3.4
Complexity in forest succession knowledge perceived by individual expert (NW Region)
Section 3.5
Among-expert variability in forest succession knowledge (NW Region)
Section 3.6
Expert group uncertainty in forest succession knowledge (NE Region)
Section 3.3
Individual expert uncertainty in forest succession knowledge (NW Region)
Section 3.7
Collective expert uncertainty in forest succession knowledge (NW Region)
Composite uncertainty in expert knowledge of forest succession (NW Region)
Section 3.8
Uncertainty in expert knowledge of forest succession
Section 3.9

Figure 14. *A guide to the presentations of results and discussion on uncertainty of expert knowledge of forest succession and its components. Note that among-expert variability in Northwest Region (Section 3.6) is a direct estimate of collective expert uncertainty, hence only presented once (NW=northwest; NE=northeast).*

3.1. Expert group confidence in forest succession knowledge in Northeast Region

3.1.1. Data summary

Levels of confidence were recorded for all reviewed transition rules, grouped by post-fire establishment and natural succession. Levels of confidence assigned to rules by experts were 1 = not confident, 2 = moderately confident, and 3 = very confident. Although experts could have assigned level 0 for unknown, they opted not to do so. For convenience, we used confidence level 0 to denote rules excluded from the review by the experts and/or those excluded from subsequent analyses due to their incomplete review. Nine transition rules were excluded for post-fire establishment and seven for natural succession. The confidence level assigned to each rule is shown in Figure 15, where the rules are ordered by priority ranking (as explained in the methods section; list provided in Appendix III).

The summaries and analyses of confidence levels assigned to rules were grouped by post-fire establishment and natural succession as illustrated in Figure 16. Measures of central tendency (mode, mean, and median) and shape (ordinal concentration indicates spread) of the overall confidence level and the distribution of confidence levels among transition rules are also provided. The reviewed forest cover transition rule set evaluated by the expert group in Northeast Region is provided in Appendix VI.

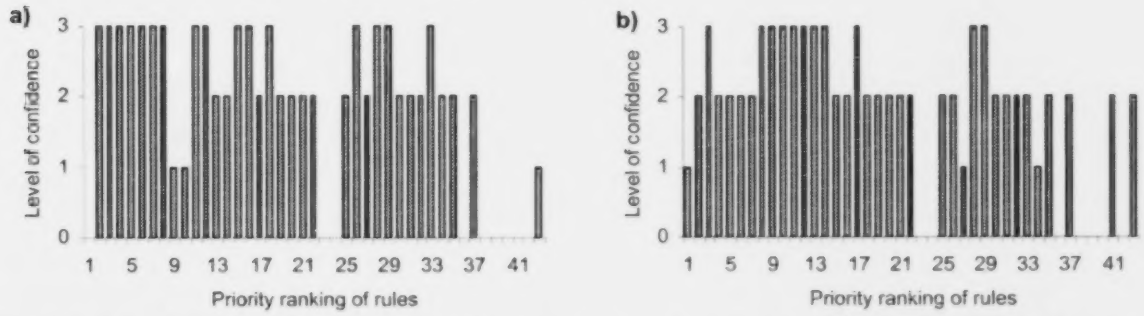

Figure 15. *The level of confidence for (a)* post-fire establishment *and (b)* natural succession *transition rules, as reviewed by the expert group in the Northeast Region. Priority ranking is in descending order of importance. Levels of confidence are 1 = not confident, 2 = moderately confident, and 3 = very confident. Confidence level 0 = unknown was used for transition rules that had to be excluded from*

3.1.2. Level of expert group confidence

Post-fire establishment

The ratio of numbers of observations in confidence level 1 to level 3 was 0.19, indicating that the distribution of confidence about post-fire establishment transition rules was skewed left (i.e., the majority of observations were to the right of centre in level 3; Figure 16a). Since the difference between the median and mean was large, skewness must be strong. Since all three levels of confidence were represented, and the median is smaller than the mode, the measure of normed ordinal concentration indicated that the left tail of the distribution was not prominent.

Natural succession

The ratio of numbers of observations in confidence level 1 to level 3 was 0.27, indicating that the distribution of expert confidence in natural succession transition rules was skewed left (Figure 16b), but weakly, since mode and median were both equal to 2 and the mean was not much larger than the median. The normed ordinal concentration indicated that observations were concentrated in the middle of the range with an unbalanced distribution over the tails.

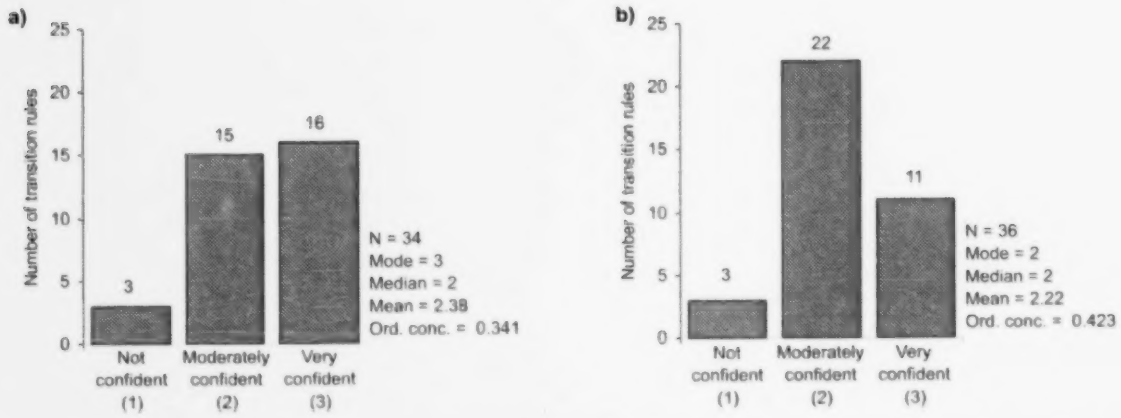

Figure 16. *Summaries of confidence values assigned to rules on (a)* post-fire establishment *and (b)* natural succession *transition by expert group in Northeast Region. (Numbers in parentheses indicate confidence levels and numbers above bars indicate the number of rules; Ord. conc. = normed ordinal concentration).*

Comparing post-fire establishment and natural succession

The ratio of numbers of observations in confidence level 1 to level 3 was smaller than 1.00, indicating the distribution was skewed to the left for both post-fire establishment and natural succession transition rules. However, the modes and medians indicated that confidence levels were stronger left-skewed for post-fire establishment rules than natural succession. The lower normed ordinal concentration for post-fire establishment rules indicated a weaker concentration in one confidence level, in comparison to natural succession rules.

Conclusions

Experts in Northeast Region were moderately to very confident in their knowledge about post-fire establishment and natural succession transition rules. However, they were relatively more confident in their knowledge of post-fire establishment transition rules.

3.1.3. Variables associated with expert group confidence

The strength of association between variability of expert group confidence and independent variables was tested separately for post-fire establishment and natural succession transition rules. The independent variables were forest unit, leaf type, moisture regime, and nutrient regime.

Post-fire establishment

Variability of expert group confidence levels showed the strongest association with forest unit, followed by nutrient regime, moisture regime, and leaf type (Table 5). However, only the association of level of confidence with forest unit was significant after sequential Bonferroni correction.

Using the confidence level assigned to the majority of transition rules as the overall confidence level, the distribution of expert group confidence levels in reviewed transition rules over the various forest units was investigated. This analysis showed that for

Table 5. *The strength of association of variability of expert group confidence in post-fire establishment transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as the Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.748***	< 0.001
Leaf type	0.123 NS	0.099
Moisture regime	0.176 NS	0.085
Nutrient regime	0.181 NS	0.075

† Theil's coefficient
NS indicates not significant at α = 0.05 after sequential Bonferroni correction
*** indicates significance at α = 0.001 after sequential Bonferroni correction

post-fire establishment rules, experts are not confident about LC1, moderately confident about PJ2, SP1, SF1 and MW1, and very confident about SB1, PJ1, PO1, BW1, and MW2 (Table 6).

Natural succession

Variability of expert group confidence levels for natural succession transition rules showed the strongest association with forest unit, followed by leaf type, nutrient regime, and moisture regime (Table 7). However, only the association of level of confidence with forest unit was significant after sequential Bonferroni correction.

The distribution of the expert group confidence levels in reviewed natural succession transition rules over the different forest units shows that experts are not confident about PJ2, not confident to moderately confident about SB1, moderately confident about SF1, BW1, MW1, and MW2, moderately confident to very confident about SP1, and very confident about PJ1, LC1, and PO1 (Table 8).

Conclusion

We conclude that expert group confidence in the Northeast region differs among forest units for both post-fire establishment and natural succession rules. Expert confidence in post-fire establishment transition rules was low for one forest unit, medium for four forest units, and high for five (Table 6). For natural succession transitions rules, expert confidence was low for one, low to medium for one, medium for four, medium to high for one, and high for three forest units (Table 8).

Table 6. *Number of reviewed post-fire establishment transition rules in each confidence level grouped by forest unit. (Forest unit codes are defined in Table 1.)*

Confidence level	Forest unit									
	SB1	PJ1	LC1	PJ2	SP1	SF1	PO1	BW1	MW1	MW2
Not confident	0	0	2	0	0	0	1	0	0	0
Moderately confident	0	0	0	2	6	4	0	1	2	0
Very confident	1	3	0	0	0	2	3	2	0	5

Table 7. *The strength of association of variability of expert group confidence in natural succession transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.679**	0.001
Leaf type	0.155 NS	0.046
Moisture regime	0.062 NS	0.695
Nutrient regime	0.100 NS	0.393

† Theil's coefficient
NS indicates not significant at α = 0.05 after sequential Bonferroni correction
** indicates significance at α = 0.01 after sequential Bonferroni correction

Table 8. *Number of reviewed natural succession transition rules in each confidence level grouped by forest unit. (Forest unit codes are defined in Table 1.)*

Confidence level	Forest unit									
	SB1	PJ1	LC1	PJ2	SP1	SF1	PO1	BW1	MW1	MW2
Not confident	1	0	0	2	0	0	0	0	0	0
Moderately confident	1	1	0	0	3	6	1	3	2	5
Very confident	0	3	2	0	3	0	3	0	0	0

3.2. Perceived complexity of forest succession knowledge by the expert group in Northeast Region

3.2.1. Data summary

Levels of perceived complexity were recorded for all reviewed transition rules, grouped by post-fire establishment and natural succession. Levels of perceived complexity assigned to rules by experts were 1 = low complexity, 2 = medium complexity, and 3 = high complexity. Although experts could have assigned level 0 for unknown, they opted not to do so. For convenience, we used complexity level 0 to denote rules excluded from the review by the experts and/or those excluded from subsequent analyses due to their incomplete review. Nine transition rules were excluded for post-fire establishment and seven for natural succession. The complexity level assigned to each rule is shown in Figure 17, where the rules are ordered by priority ranking (as explained in the methods section).

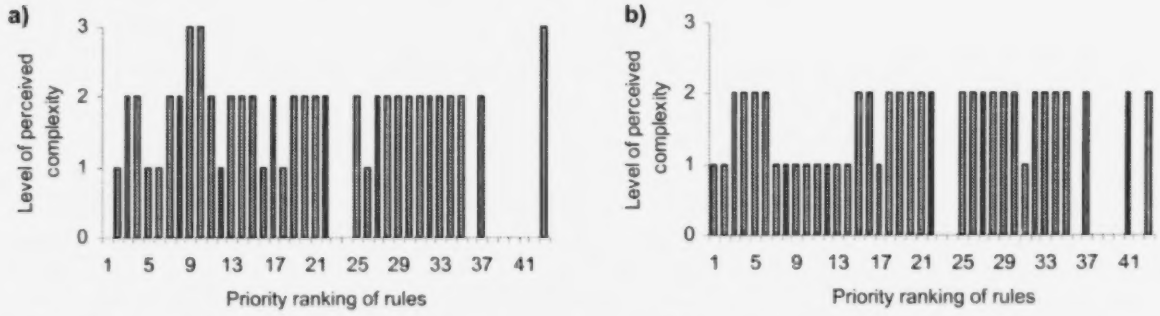

Figure 17. *The level of perceived complexity for (a)* post-fire establishment *and (b)* natural succession *transition rules, as reviewed by the expert group in the Northeast Region. Priority ranking is in descending order of importance. Levels of complexity are 1 = low complexity, 2 = medium complexity, and 3 = high complexity. Complexity level 0 = unknown was used for transition rules that had to be excluded from the study.*

The summaries and analyses of levels of perceived complexity assigned to rules were grouped by post-fire establishment and natural succession as illustrated in Figure 18. Measures of central tendency (mode, mean, and median) and shape (ordinal concentration indicates spread) of the overall complexity level and the distribution of complexity levels among transition rules are also provided.

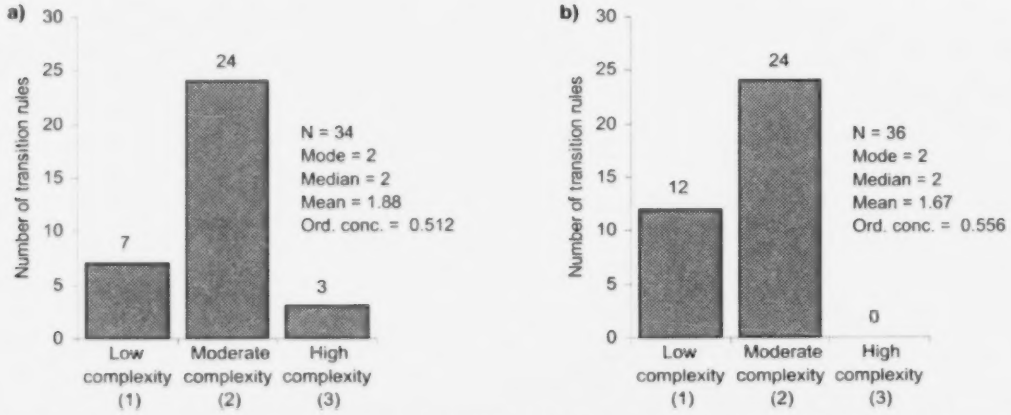

Figure 18. *Summaries of values of perceived complexity assigned to rules on (a)* post-fire establishment *and (b)* natural succession *transition by expert group in Northeast Region. (Numbers in parentheses indicate complexity levels and numbers above bars indicate the number of rules; Ord. conc. = normed ordinal concentration).*

3.2.2. Level of perceived complexity

Post-fire establishment

The ratio of numbers of observations in complexity level 1 to level 3 was 2.33, indicating that the distribution of perceived complexity of post-fire establishment transition rules was skewed right (i.e., the majority of observations are to the left of the centre in level 1), but not strongly as indicated by the small difference between the median and mean (Figure 18a). Since all three levels of complexity were represented, and the median value is equal to the modal value, the measure of normed ordinal concentration indicated relatively balanced tails and a clear concentration of values in level 2.

Natural succession

The ratio of numbers of observations in complexity level 1 to level 3 was not defined since there are no observations in level 3 (Figure 18b). Therefore, the distribution of perceived complexity of natural succession transition rules must be skewed right. Since only two levels of complexity were represented, the normed ordinal concentration indicated that one of the levels of confidence was more prominent then the other.

Comparing post-fire establishment and natural succession

The ratio of number of observations in complexity level 1 to level 3 indicated that the distribution was skewed right for both post-fire establishment and natural succession transition rules. However, the larger differences between mean and median and the missing level 3 for natural succession indicated that levels of perceived complexity were lower for natural succession than for post-fire establishment.

Conclusion

Experts in Northeast Region perceived complexity to be mostly medium for both post-fire establishment and natural succession forest cover transition rules. However, perceived complexity varied more for post-fire establishment than for natural succession and tended to be lower for natural succession transition rules.

3.2.3. Variables associated with perceived complexity

The strength of association between variability of perceived complexity at the expert group level and independent variables was tested separately for post-fire establishment and natural succession transition rules. The independent variables were forest unit, leaf type, moisture regime, and nutrient regime.

Post-fire establishment

Variability of perceived complexity levels for post-fire establishment transition rules showed the strongest association with forest unit, followed by nutrient regime, moisture regime, and leaf type (Table 9). However, none of the associations with the independent variables was significant after sequential Bonferroni correction.

Natural succession

Variability of perceived complexity levels of natural succession transition rules showed the strongest association with forest unit, followed by nutrient regime, moisture regime, and leaf type (Table 10). All of the associations were significant after sequential Bonferroni correction at $\alpha = 0.05$ or better.

Table 9. *The strength of association of variability of perceived complexity at the expert group level of post-fire establishment transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.546 ^{NS}	0.047
Leaf type	0.065 ^{NS}	0.481
Moisture regime	0.252 ^{NS}	0.036
Nutrient regime	0.260 ^{NS}	0.031

† Theil's coefficient
NS indicates not significant at α = 0.05 after sequential Bonferroni correction

Table 10. *The strength of association of variability of perceived complexity at the expert group level of natural succession transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.626**	0.001
Leaf type	0.209*	0.008
Moisture regime	0.275*	0.006
Nutrient regime	0.483***	< 0.001

† Theil's coefficient
* indicates significance at α = 0.05 after sequential Bonferroni correction
** indicates significance at α = 0.01 after sequential Bonferroni correction
*** indicates significance at α = 0.001 after sequential Bonferroni correction

The distribution of levels of perceived complexity of natural succession transition rules reviewed by the expert group over the different forest units shows that complexity is considered low for SB1, PJ1, LC1, and SP1 and medium for PJ2, SF1, PO1, BW1, MW1, and MW2 (Table 11).

Table 11. *Number of reviewed natural succession transition rules in each perceived complexity level grouped by forest unit. (Forest unit codes are defined in Table 1.)*

Complexity level	Forest unit									
	SB1	PJ1	LC1	PJ2	SP1	SF1	PO1	BW1	MW1	MW2
Low complexity	2	3	2	0	4	0	0	0	0	1
Medium complexity	0	1	0	2	2	6	4	3	2	4
High complexity	0	0	0	0	0	0	0	0	0	0

The distribution of levels of perceived complexity of reviewed natural succession transition rules over the different nutrient regimes shows that complexity is considered low for poor and organic sites and medium for mesotrophic and rich sites (Table 12).

The distribution of levels of perceived complexity of reviewed natural succession transition rules over the different moisture regimes shows that experts consider complexity low for saturated sites and medium for dry, mesic, and wet sites (Table 13).

Table 12. *Number of reviewed natural succession transition rules in each perceived complexity level grouped by nutrient regime.*

Complexity level	Nutrient regime			
	Poor	Mesotrophic	Rich	Organic
Low complexity	2	6	0	4
Medium complexity	0	13	11	0
High complexity	0	0	0	0

Table 13. *Number of reviewed natural succession transition rules in each perceived complexity level grouped by moisture regime.*

Complexity level	Moisture regime			
	Dry	Mesic	Wet	Saturated
Low complexity	5	2	1	4
Medium complexity	7	11	6	0
High complexity	0	0	0	0

The distribution of levels of perceived complexity of reviewed natural succession transition rules over the different leaf type groups shows that complexity is considered low to medium for conifer and medium for mixedwood and hardwood (Table 14).

Table 14. *Number of reviewed natural succession transition rules in each perceived complexity level grouped by leaf type.*

Complexity level	Leaf type		
	conifer	mixedwood	hardwood
Low complexity	11	1	0
Medium complexity	11	6	7
High complexity	0	0	0

Conclusion

We conclude that perceived complexity of forest succession knowledge of the expert group differs among forest units, nutrient regime, moisture regime, and leaf type for natural succession but not for post-fire establishment transition rules. For natural succession transition rules, perceived complexity was low for four forest units and medium for six forest units (Table 11). Complexity was ranked low for more extreme site conditions than for medium site conditions (nutrient and moisture regimes, Tables 12 and 13), and was lower for coniferous forest units than for mixedwood and hardwood forest units (Table 14).

3.3. Uncertainty in expert group knowledge of forest succession in Northeast Region

3.3.1. Data summary

Levels of expert group knowledge uncertainty were derived for all reviewed transition rules, grouped by post-fire establishment and natural succession (Figure 19). Expert group knowledge uncertainty was estimated by expert group knowledge confidence (*Lc*=not confident; *Mc*=moderately confident; *Hc*=very confident) and perceived complexity of expert group knowledge (*Lx*=low; *Mx*=medium; *Hx*=high), that we assessed earlier (see Sections 3.1 and 3.2). Expert group confidence and perceived complexity values were combined using the rank-weight matrix (see Figure 8) to derive the levels of expert group uncertainty. The resulting levels of uncertainty assigned to rules were low, medium, and high, as illustrated in Figure 19. For post fire establishment, 16 transition rules were in low; 0 in medium; and 18 in high uncertainty categories. For natural succession, 11 transition rules were in low; 3 in medium; and 22 in high uncertainty categories.

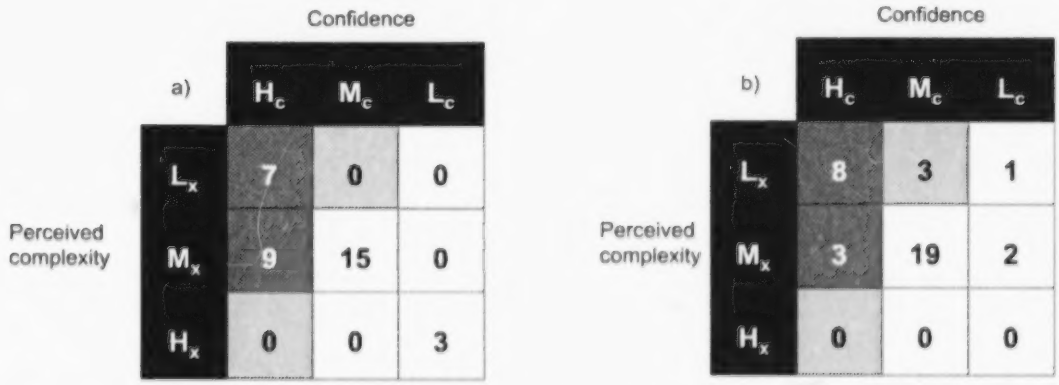

Figure 19. *The number of transition rules in categories of expert group uncertainty, derived from expert group confidence and perceived complexity in forest succession knowledge for (a)* post-fire establishment *and (b)* natural succession *transition rules in the Northeast Region. The numbers in each cell indicate the number of transition rules for the row (complexity)-column (confidence) combination. Confidence level is Lc=not confident, Mc=moderately confident, Hc=very confident; perceived complexity level is Lx=low, Mx=medium, Hx=high. Levels of uncertainty are low uncertainty (dark gray), medium uncertainty (light gray), and high uncertainty (white).*

The uncertainty level assigned to each rule is shown Figure 20, where the rules are ordered according to priority ranking (as explained in the methods section). Values assigned to uncertainty levels were 1 = low, 2 = medium, 3 = high. For convenience, we used uncertainty level 0 to denote the nine post-fire transition rules and seven natural succession transition rules excluded from analyses due to their incomplete review by experts.

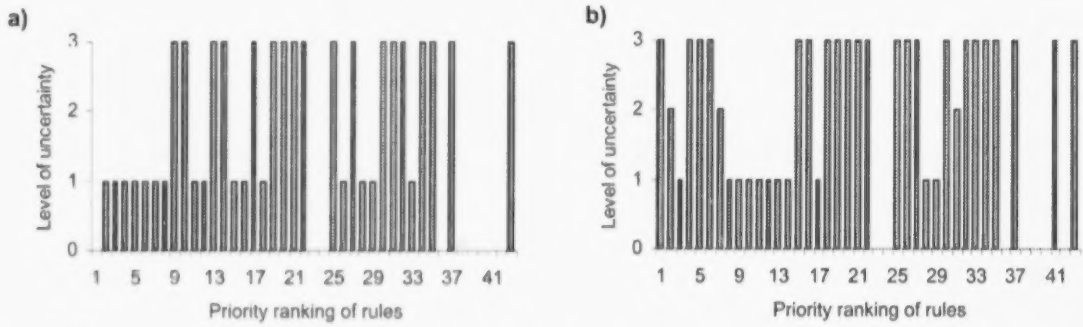

Figure 20. *The level of uncertainty for (a) post-fire establishment and (b) natural succession transition rules, as derived for the expert group in the Northeast Region. Priority ranking is in descending order of importance. Levels of uncertainty are 1 = low, 2 = medium, and 3 = high. Uncertainty level 0 = unknown was used for transition rules that had to be excluded from the study.*

The summaries and analyses of levels of uncertainty assigned to rules were grouped by post-fire establishment and natural succession as illustrated in Figure 21. Measures of central tendency (mode, mean, and median) and shape (ordinal concentration indicates spread) of the overall uncertainty level and the distribution of uncertainty levels among transition rules are also provided.

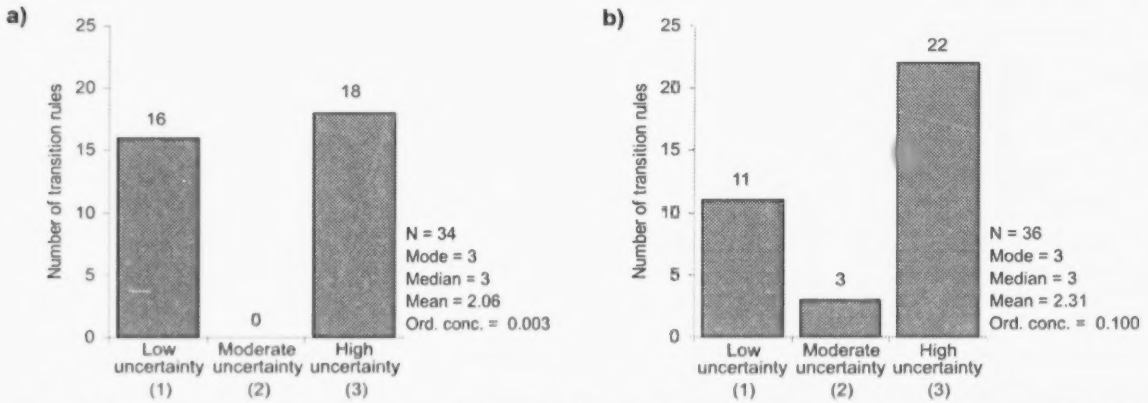

Figure 21. *Summaries of values of uncertainty assigned to rules on (a) post-fire establishment and (b) natural succession transition for expert group in Northeast Region. (Numbers in parentheses indicate uncertainty levels and numbers above bars indicate the number of rules; Ord. conc. = normed ordinal concentration).*

3.3.2. Level of uncertainty in expert group knowledge

Post-fire establishment

The ratio of numbers of observations in level 1 to level 3 was 0.89, indicating that the distribution of uncertainty about post-fire establishment transition rules was skewed left (Figure 20a). However, the normed ordinal concentration is 0.003, indicating a strongly bimodal distribution. Visual investigation of the distribution (Figure 21a) shows that there are no observations in level 2, confirming the bimodal distribution. Despite the level 1 to level 3 ratio of 0.89 and the median value of 3, the values of the mean and normed ordinal concentration indicate near equal proportions of observations in levels 1 and 3.

Natural succession

The ratio of numbers of observations in level 1 to level 3 was 0.50, indicating that the distribution of confidence about natural succession transition rules was skewed left (Figure 21b). However, the normed ordinal concentration is 0.100. This value can indicate a bimodal distribution or a near equal distribution of observations over all three levels (see methods section).

Comparing post-fire establishment and natural succession

The normed ordinal concentration value was low for both post-fire establishment and natural succession transition rules, indicating bimodal distributions. The smaller difference between the mean and median for natural succession than for post-fire establishment indicated a higher peak in level 3 in the case of natural succession.

Conclusions

Expert group uncertainty for both knowledge about post-fire establishment and natural succession forest cover transition rules is mostly low or high. Uncertainty about natural succession is higher than that for post-fire establishment transition rules. A summary of results that led to the expert group uncertainty in Northeast Region is illustrated in Figure 22.

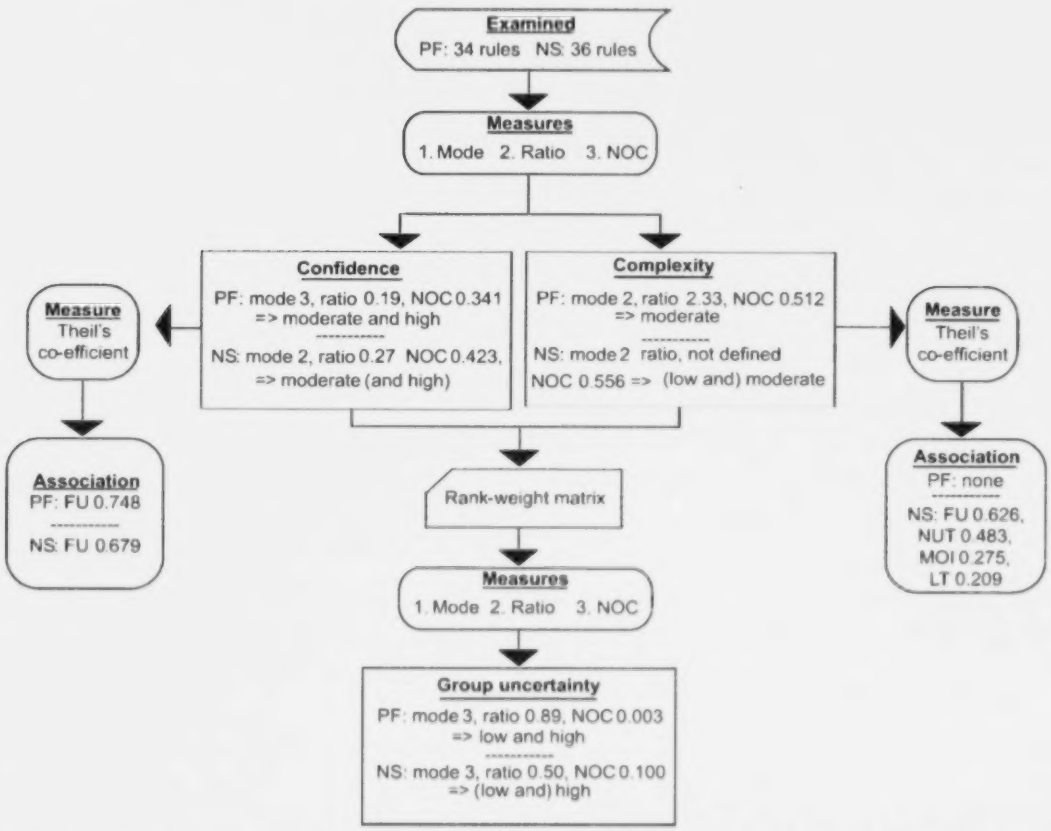

Figure 22. *A summary of results from the data analyses of the components of expert group uncertainty in forest succession knowledge of individual experts in Northwest Region (PF= post-fire establishment transition rules, NS= natural succession transition rules, Ratio= ratio of numbers of observations in extreme levels (low:high), NOC= normed ordinal concentration, FU= forest unit, LT= leaf type group, MOI= moisture regime, NUT= nutrient regime).*

3.4. Individual expert confidence in forest succession knowledge in Northwest Region

3.4.1. Data summary

Levels of confidence were recorded for all reviewed transition rules, grouped by post-fire establishment and natural succession. Levels of confidence assigned to rules by experts were 1 = not confident, 2 = moderately confident, and 3 = very confident. Although experts could have assigned level 0 for unknown, they opted not to do so. For convenience, we used confidence level 0 to denote rules excluded from the review by the experts and/or those excluded from subsequent analyses due to their incomplete review. Two transition rules were excluded for natural succession. While the full priority list of transition rules was longer than what is shown here, transition rules with priority ranking larger than 39 were not reviewed by all experts. These rules were therefore excluded from further analysis. The confidence level assigned to each rule is shown Figure 23, where the rules are ordered by priority ranking (as explained in the methods section; list provided in Appendix IV).

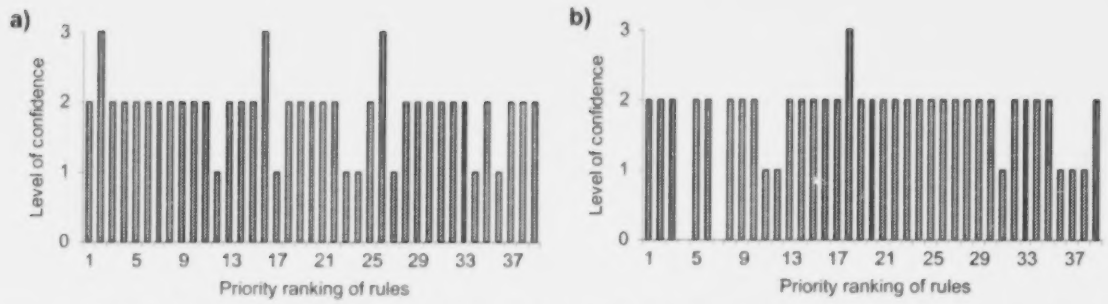

Figure 23. *The level of confidence for (a)* post-fire establishment *and (b)* natural succession *transition rules, as reviewed by individual experts in the Northwest Region. Priority ranking is in descending order of importance. Levels of confidence are 1 = not confident, 2 = moderately confident, and 3 = very confident. Confidence level 0 = unknown was used for transition rules that had to be excluded from the study.*

The summaries and analyses of confidence levels assigned to rules were grouped by post-fire establishment and natural succession as illustrated in Figure 24. Measures of central tendency (mode, mean, and median) and shape (ordinal concentration indicates spread) of the overall confidence level and the distribution of confidence levels among transition rules are also provided. The reviewed forest cover transition rule set evaluated by individual experts in Northwest Region is provided in Appendix VII.

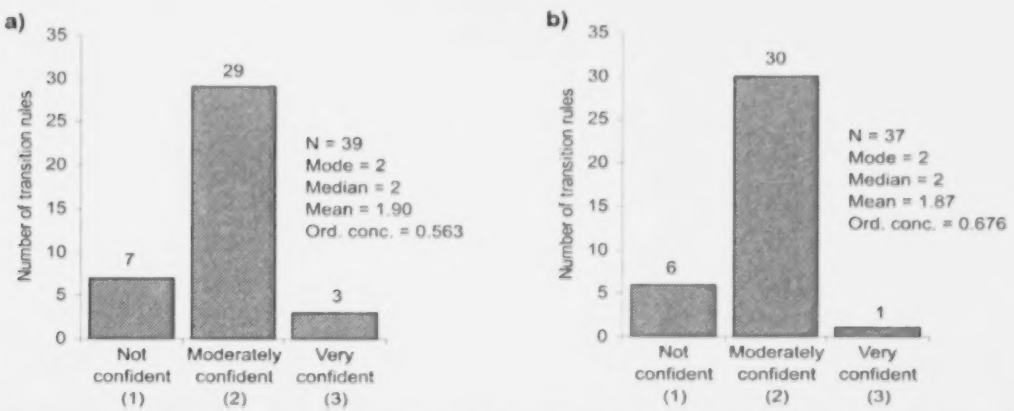

Figure 24. *Summaries of confidence values assigned to rules on (a)* post-fire establishment *and (b)* natural succession *transition by individual experts in Northwest Region. (Numbers in parentheses indicate confidence levels and numbers above bars indicate the number of rules; Ord. conc. = normed ordinal concentration).*

3.4.2. Level of individual expert confidence

Post-fire establishment

The ratio of numbers of observations in confidence level 1 to level 3 was 2.33, indicating a right-skewed distribution of confidence in post-fire establishment transition rules (Figure 24a). However, the skewness can only be weak as indicated by the small difference between the median and mean values. The measure of normed ordinal concentration indicated a clear dominance of the median class over the tails of the distribution.

Natural succession

The ratio of numbers of observations in confidence level 1 to level 3 was 6.00, indicating that the distribution of confidence in natural succession transition rules must be skewed right, but weakly so since the mode and median

were equal and the mean was not much smaller than the median (Figure 24b). The normed ordinal concentration indicated a strong dominance of the median class over the two tails.

Comparing post-fire establishment and natural succession

The ratio of numbers of observations in confidence level 1 to level 3 was larger than 1.00, indicating the distribution was skewed to the right for both post-fire establishment and natural succession transition rules. However, the difference between median and mean was not large in either case, indicating relatively small absolute differences between the tails of the distributions. The higher normed ordinal concentration for natural succession rules indicated a stronger concentration in the median confidence level, compared to post-fire establishment rules.

Conclusion

Expert confidence in their knowledge varied from not confident to very confident for both post-fire establishment and natural succession transition rules, but was mostly medium.

3.4.3. Variables associated with individual expert confidence

The strength of association between variability of expert group confidence and independent variables was tested separately for post-fire establishment and natural succession transition rules. The independent variables were forest unit, leaf type, moisture regime, and nutrient regime.

Post-fire establishment

Variability of confidence levels for post-fire establishment transition rules showed the strongest association with forest unit, followed by leaf type, moisture regime, and nutrient regime (Table 15). However, none of the associations of level of confidence with any of the independent variables was significant after sequential Bonferroni correction.

Natural succession

Variability of confidence levels for natural succession transition rules showed the strongest association with forest unit, followed by moisture regime, nutrient regime, and leaf type (Table 16). However, none of the associations of level of confidence with any of the independent variables was significant after sequential Bonferroni correction.

Conclusion

No pattern emerged from analysis of independent variables that could explain the variation in confidence in knowledge about post-fire establishment or succession for individual experts in Northwest Region.

Table 15. *The strength of association of variability of individual expert confidence in post-fire establishment transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.465 ^{NS}	0.023
Leaf type	0.167 ^{NS}	0.051
Moisture regime	0.049 ^{NS}	0.249
Nutrient regime	0.022 ^{NS}	0.874

† Theil's coefficient
NS indicates not significant at α = 0.05 after sequential Bonferroni correction

Table 16. *The strength of association of variability of individual expert confidence in natural succession transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.221 ^{NS}	0.819
Leaf type	0.097 ^{NS}	0.399
Moisture regime	0.147 ^{NS}	0.047
Nutrient regime	0.100 ^{NS}	0.385

† Theil's coefficient
NS indicates not significant at α = 0.05 after sequential Bonferroni correction

3.5. Perceived complexity of forest succession knowledge by individual experts in Northwest Region

3.5.1. Data summary

Levels of complexity were recorded for all reviewed transition rules, grouped by post-fire establishment and natural succession. Levels of perceived complexity assigned to rules by experts were 1 = low complexity, 2 = medium complexity, and 3 = high complexity. Although experts could have assigned level 0 for unknown, they opted not to do so. For convenience, we used complexity level 0 to denote rules excluded from the review by the experts and/or those excluded from subsequent analyses due to incomplete review. Two transition rules were excluded for natural succession. The full priority list of transition rule was longer than what is shown here, however, none of the transition rules with priority ranking larger than 39 was completely reviewed by all experts. These rules are therefore excluded from further analysis. The confidence level assigned to each rule is shown Figure 25, where the rules are ordered by priority ranking (as explained in the methods section).

The summaries and analyses of complexity levels assigned to rules were grouped by post-fire establishment and natural succession as illustrated in Figure 26. Measures of central tendency (mode, mean, and median) and shape (ordinal concentration indicates spread) of the overall complexity level and the distribution of complexity levels among transition rules are also provided.

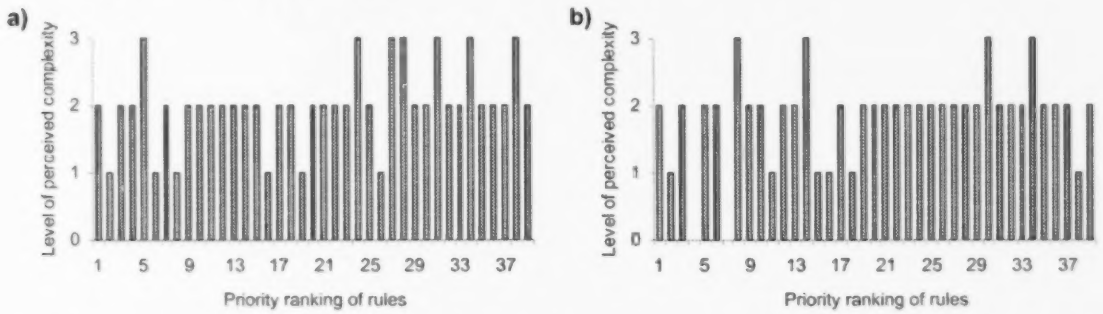

Figure 25. *The level of perceived complexity for (a)* post-fire establishment *and (b)* natural succession *transition rules, as reviewed by individual experts in the Northwest Region. Priority ranking is in descending order of importance. Levels of confidence are 1 = not confident, 2 = moderately confident, and 3 = very confident. Confidence level 0 = unknown was used for transition rules that had to be excluded from the study.*

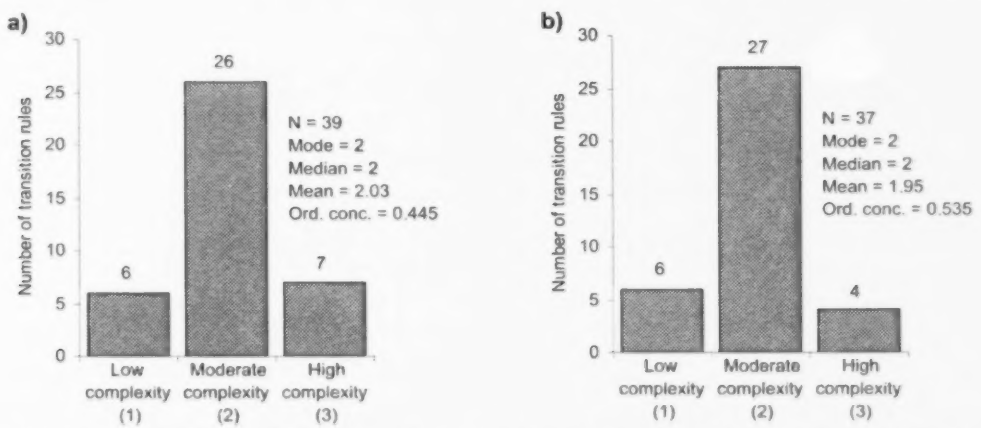

Figure 26. *Summaries of values of perceived complexity assigned to rules on (a)* post-fire establishment *and (b)* natural succession *transition by individual experts in Northwest Region. (Numbers in parentheses indicate complexity levels and numbers above bars indicate the number of rules; Ord. conc. = normed ordinal concentration).*

3.5.2. Level of perceived complexity

Post-fire establishment

The ratio of numbers of observations in complexity level 1 to level 3 was 0.86, indicating a left-skewed distribution of perceived complexity of post-fire establishment transition rules (Figure 26a). However, since the mean is almost identical to the median, the skewness must be very weak. Since all three levels of complexity were represented, and the distribution is only very weakly skewed, the measure of normed ordinal concentration indicated a clear concentration of values in level 2.

Natural succession

The ratio of numbers of observations in complexity level 1 to level 3 was 1.50 indicating a right-skewed distribution of perceived complexity of natural succession transition rules (Figure 26b). However, the distribution must be skewed only slightly since the difference between mean and median is very small. Since all three levels of complexity were represented, and the distribution is hardly skewed, the measure of normed ordinal concentration indicated a strong concentration of values in level 2.

Comparing post-fire establishment and natural succession

The mean of complexity level was very close to the median, indicating little skewness of the distribution for both post-fire establishment and natural succession transition rules. However, the larger value of the normed ordinal concentration for natural succession indicated a slightly stronger concentration of perceived complexity at the median level for natural succession compared to post-fire establishment.

Conclusion

Individual experts in Northwest Region perceived complexity to vary from low to high, but mostly ranked it medium for both post-fire establishment and natural succession. Perceived complexity was more concentrated at the medium level for natural succession than for post-fire establishment.

3.5.3. Variables associated with perceived complexity

The strength of association between variability of perceived complexity at the individual expert level and independent variables was tested separately for post-fire establishment and natural succession transition rules. The independent variables were forest unit, leaf type, moisture regime, and nutrient regime.

Post-fire establishment

Variability of complexity levels for post-fire establishment transition rules showed the strongest association with forest unit, followed by leaf type, nutrient regime, and moisture regime (Table 17). However, none of the associations of level of complexity with any of the independent variables was significant after sequential Bonferroni correction.

Natural succession

Variability of complexity levels for natural succession transition rules showed the strongest association with forest unit, followed by nutrient regime, leaf type, and moisture regime (Table 18). However, none of the associations of level of complexity with any of the independent variables was significant after sequential Bonferroni correction.

Table 17. *The strength of association of variability of perceived complexity at the individual expert level for post-fire establishment transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.415 ^{NS}	0.014
Leaf type	0.165 ^{NS}	0.025
Moisture regime	0.024 ^{NS}	0.440
Nutrient regime	0.064 ^{NS}	0.561

† Theil's coefficient
NS indicates not significant at α = 0.05 after sequential Bonferroni correction

Table 18. *The strength of association of variability of perceived complexity at the individual expert level for natural succession transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.295 ^{NS}	0.273
Leaf type	0.044 ^{NS}	0.647
Moisture regime	0.042 ^{NS}	0.307
Nutrient regime	0.149 ^{NS}	0.077

† Theil's coefficient
NS indicates not significant at α = 0.05 after sequential Bonferroni correction

Conclusion

None of the independent variables investigated could explain the variation in perceived complexity in individual expert knowledge of post-fire establishment or natural succession transition in Northwest Region.

3.6. Among-expert variability in knowledge of forest succession in Northwest Region

3.6.1. Data summary

Levels of among-expert variability were recorded for all reviewed transition rules, grouped by post-fire establishment and natural succession. Levels of variability assigned to rules were 1 = all rules identical, 2 = two rules different, 3 = three rules different, and 4 = all rules different. For convenience, we used variability level 0 to denote rules excluded from the review by the experts and/or those excluded from subsequent analyses due to their incomplete review. Six transition rules were excluded for post-fire establishment and four transition rules were excluded for natural succession. The full priority list of transition rules was longer than what is shown here. However, none of the transition rules with priority ranking larger than 39 was completely reviewed by all experts. These rules are therefore excluded from further analysis and not included here. The confidence level assigned to each rule is shown Figure 27, where the rules are ordered according to priority ranking (as explained in the methods section).

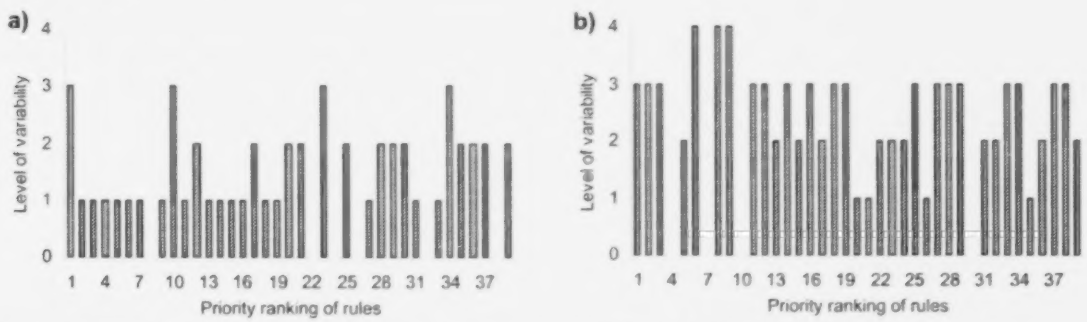

Figure 27. *The level of among-expert variability for (a)* post-fire establishment *and (b)* natural succession *transition rules, as reviewed by individual experts in the Northwest Region. Priority ranking is in descending order of importance. Levels of variability are 1 = all rules identical, 2 = two rules different, 3 = three rules different, and 4 = all rules different. Variability level 0 = unknown was used for transition rules that had to be excluded from the study.*

The summaries and analyses of variability levels assigned to rules were grouped by post-fire establishment and natural succession as illustrated in Figure 28. Measures of central tendency (mode, mean, and median) and shape (ordinal concentration indicates spread) of the overall variability level and the distribution of variability levels among transition rules are also provided.

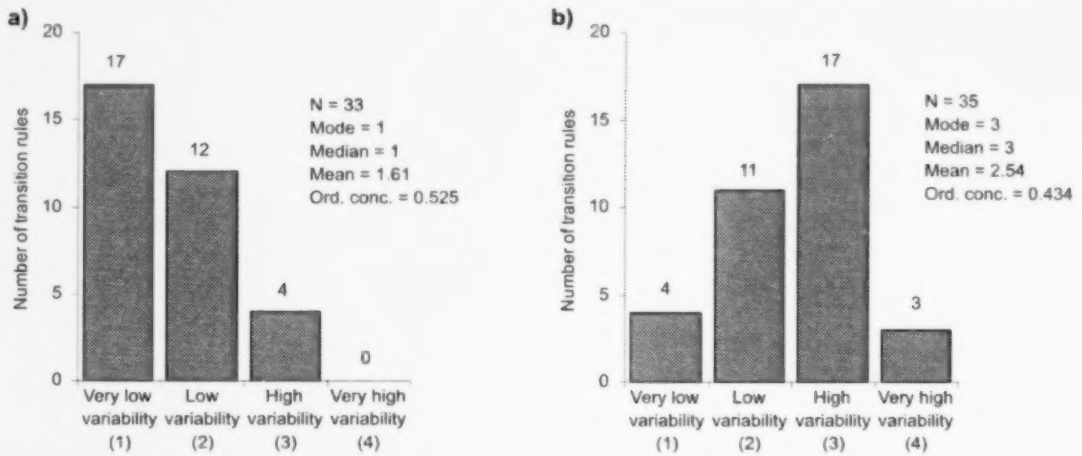

Figure 28. *Summaries of values of among-expert variability assigned to rules on (a)* post-fire establishment *and (b)* natural succession *transition in Northwest Region. (Numbers in parentheses indicate variability levels and numbers above bars indicate the number of rules; Ord. conc. = normed ordinal concentration).*

3.6.2. Level of among-expert variability

Post-fire establishment

The ratio of numbers of observations in levels 1 and 2 to levels 3 and 4 was 7.25, indicating a right-skewed distribution of among-expert variability for post-fire establishment transition rules (Figure 28a). Since the difference between the mean and median is large, the distribution must be strongly skewed. Given that the median lies in one of the extreme levels (level 1) and that one of the levels is not represented (level 4), the value of the normed ordinal concentration indicated that the distribution of values is skewed towards the extreme median class, but that a large proportion of observations was found in levels 2 and 3.

Natural succession

The ratio of numbers of observations in levels 1 and 2 to levels 3 and 4 was 0.75, indicating a left-skewed distribution of among-expert variability for natural succession transition rules (Figure 28b). Since the difference between the mean and median is large, the distribution must be strongly skewed. Given that the median lies in one of the centre levels, the value of the normed ordinal concentration indicated that the distribution had relatively fat tails.

Comparing post-fire establishment and natural succession

The ratio of numbers of observations in levels 1 and 2 to levels 3 and 4 was larger than 1.00 for post-fire establishment transition rules and was smaller than 1.00 for natural succession transition rules, indicating skewness to opposite directions. The difference between the mean and median and the range of among-expert variability for post-fire establishment transition rules were smaller than those for natural succession rules.

Conclusion

The among-expert variability in knowledge ranged from very low to high for post-fire establishment transition rules and from very low to very high for natural succession knowledge. Variability was higher for natural succession than for post-fire establishment transition rules.

3.6.3. Variables associated with among-expert variability

The strength of association between among-expert variability for individual experts and independent variables was tested separately for post-fire establishment and natural succession transition rules. The independent variables were forest unit, leaf type, moisture regime, and nutrient regime.

Post-fire establishment

Among-expert variability in post-fire establishment transition rules showed the strongest association with forest unit, followed by leaf type, moisture regime, and nutrient regime (Table 19). The associations of level of variability with forest unit and with leaf type were significant after sequential Bonferroni correction.

The distribution of levels of among-expert variability for reviewed post-fire establishment transition rules over the different forest units shows that variability is very low for PjDom, very low to low for PjMx1 and BwDom, low for SbDom and PoDom, and high for BfDom and HrdMw (Table 20).

Table 19. *The strength of association of among-expert variability for post-fire establishment transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.459*	0.004
Leaf type	0.283**	0.001
Moisture regime	0.044 NS	0.250
Nutrient regime	0.021 NS	0.508

† Theil's coefficient
NS indicates not significant at α = 0.05 after sequential Bonferroni correction
* indicates significance at α = 0.05 after sequential Bonferroni correction
** indicates significance at α = 0.01 after sequential Bonferroni correction

Table 20. *Number of reviewed post-fire establishment transition rules in each among-expert variability level grouped by forest unit. (Forest unit codes are defined in Table 2.)*

Complexity level	Forest unit						
	PjDom	PjMx1	SbDom	BfDom	PoDom	BwDom	HrdMw
Very low variability	8	3	4	0	1	1	0
Low variability	0	3	5	0	3	1	0
High variability	0	0	1	1	0	0	2
Very high variability	0	0	0	0	0	0	0

The distribution of levels of among-expert variability for reviewed post-fire establishment transition rules over the different leaf types shows that variability is very low for conifer, low for hardwood, and high for mixedwood (Table 21).

Table 21. *Number of reviewed post-fire establishment transition rules in each among-expert variability level grouped by leaf type.*

Variability level	Leaf type		
	Conifer	Mixedwood	Hardwood
Very low variability	15	0	2
Low variability	8	0	4
High variability	1	3	0
Very high variability	0	0	0

Natural succession

Variability of among-expert variability for natural succession transition rules showed the strongest association with forest unit, followed by leaf type, moisture regime, and nutrient regime (Table 22). However, none of the associations with any of the independent variables was significant after sequential Bonferroni correction.

Table 22. *The strength of association of among-expert variability for natural succession transition rules with the independent variables (forest unit, leaf type, moisture regime, and nutrient regime) expressed as Theil's coefficient. P-values are asymptotic values estimated as the ratio of strength of association with asymptotic standard error.*

Independent variable	Strength of association†	Significance level (P)
Forest unit	0.341 NS	0.165
Leaf type	0.056 NS	0.615
Moisture regime	0.044 NS	0.323
Nutrient regime	0.036 NS	0.822

† Theil's coefficient
NS indicates not significant at α = 0.05 after sequential Bonferroni correction

Conclusion

We conclude that among-expert variability differs among forest units and leaf type for post-fire establishment, but not for natural succession transition rules. For post-fire establishment transition rules, among-expert variability was very low for one forest unit, very low to low for two forest units, low for two forest units, and high for two forest units (Table 20). Among-expert variability was lower for coniferous forest units than for hardwood and mixedwood forest units (Table 21).

3.7. Uncertainty in individual expert knowledge of forest succession in Northwest Region

3.7.1. Data summary

Levels of individual expert knowledge uncertainty were derived for all reviewed transition rules, grouped by post-fire establishment and natural succession (Figure 29). Individual expert knowledge uncertainty was estimated by individual expert knowledge confidence (*Lc*=not confident; *Mc*=moderately confident; *Hc*=very confident) and perceived complexity of individual expert knowledge (*Lx*=low; *Mx*=medium; *Hx*=high), that we assessed earlier (see Sections 3.4 and 3.5). Individual expert confidence and perceived complexity values were combined using the rank-weight matrix (see Figure 8) to derive the levels of individual expert uncertainty. The resulting levels of uncertainty assigned to rules were low, medium, and high, as illustrated in Figure 29. For post-fire establishment, three transition rules were in low, three in medium, and 33 in high uncertainty categories. For natural succession, one transition rule was in low, three in medium; and 33 in high uncertainty categories.

a)

Perceived complexity \ Confidence	H_c	M_c	L_c
L_x	3	3	0
M_x	0	22	4
H_x	0	4	3

b)

Perceived complexity \ Confidence	H_c	M_c	L_c
L_x	1	3	2
M_x	0	23	4
H_x	0	4	0

Figure 29. *The number of transition rules in categories of individual expert uncertainty, derived from individual expert confidence and perceived complexity in forest succession knowledge for (a)* post-fire establishment *and (b)* natural succession transition *rules in the Northwest Region. The numbers in each cell indicate the number of transition rules for the row (complexity)-column (confidence) combination. Confidence level is* Lc=*not confident,* Mc=*moderately confident,* Hc=*very confident; perceived complexity level is* Lx=*low,* Mx=*medium,* Hx=*high. Levels of uncertainty are low uncertainty (dark gray), medium uncertainty (light gray), and high uncertainty (white).*

The uncertainty level assigned to each rule is shown Figure 30, where the rules are ordered according to priority ranking (as explained in the methods section). Values assigned to uncertainty levels were 1 = low uncertainty, 2 = medium uncertainty, 3 = high uncertainty. For convenience, we used uncertainty level 0 to denote the two natural succession transition rules excluded from analyses due to their incomplete review by experts.

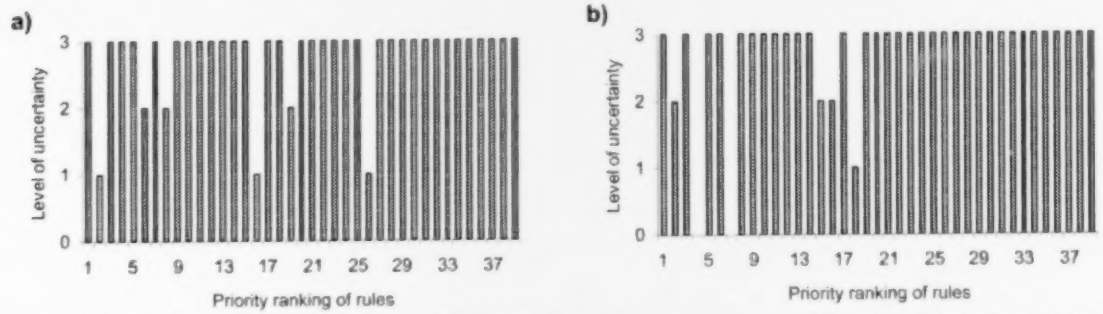

Figure 30. *The levels of uncertainty for (a) post-fire establishment and (b) natural succession transition rules, as derived for individual experts in the Northwest Region. Priority ranking is in descending order of importance. Levels of uncertainty are 1 = low, 2 = medium, and 3 = high. Uncertainty level 0 = unknown was used for transition rules that had to be excluded from the study.*

The summaries and analyses of levels of uncertainty assigned to rules were grouped by post-fire establishment and natural succession as illustrated in Figure 31. Measures of central tendency (mode, mean, and median) and shape (ordinal concentration indicates spread) of the overall uncertainty level and the distribution of uncertainty levels among transition rules are also provided.

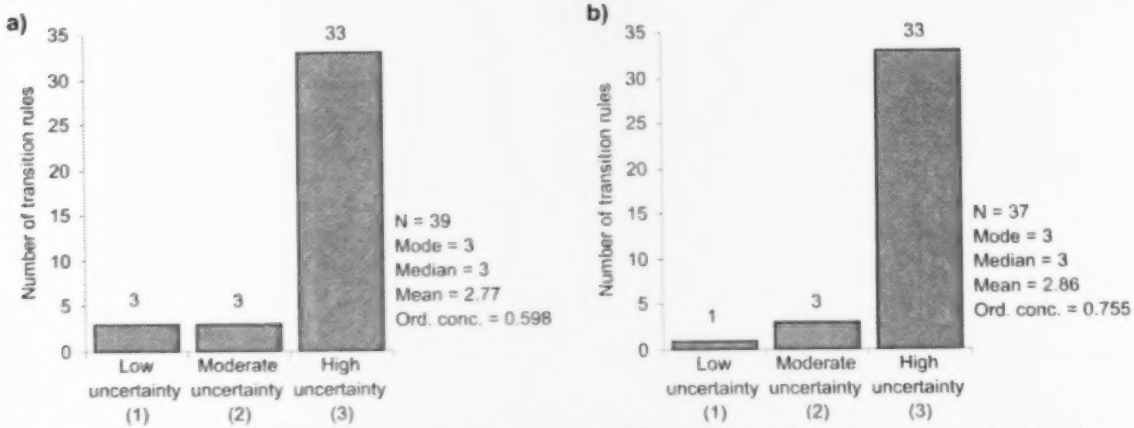

Figure 31. *Summaries of values of uncertainty assigned to rules on (a)* post-fire establishment *and (b)* natural succession *transition by experts in Northwest Region. (Numbers in parentheses indicate uncertainty levels and numbers above bars indicate the number of rules; Ord. conc. = normed ordinal concentration).*

3.7.2. Level of uncertainty in individual expert knowledge

Post-fire establishment

The ratio of numbers of observations in level 1 to level 3 was 0.09, indicating that the distribution of uncertainty about post-fire establishment transition rules was skewed left (Figure 31a). The left tail of the distribution cannot be very strong since the difference between the mean and median is small. The normed ordinal concentration indicates the dominance of median level 3 over the two other levels.

Natural succession

The ratio of numbers of observations in level 1 to level 3 was 0.03, indicating that the distribution of confidence about natural succession transition rules was skewed left (Figure 31b). The left tail of the distribution cannot be very strong since the difference between the mean and median is small. The normed ordinal concentration indicates the strong dominance of median level 3 and a very weak level 1.

Comparing post-fire establishment and natural succession

The median, range, and mean of uncertainty of knowledge about post-fire establishment and natural succession are similar or identical, indicating little difference in the distributions. The larger value of the normed ordinal concentration for uncertainty of natural succession knowledge compared to post-fire establishment indicates a stronger concentration of observations in the median level 3 for natural succession.

Conclusions

Individual expert uncertainty tends to be high for expert knowledge about both post-fire establishment and natural succession in Northwest Region.

3.8. Composite uncertainty in individual expert knowledge of forest succession in Northwest Region

3.8.1. Data summary

Levels of composite knowledge uncertainty for experts were derived for all reviewed transition rules, grouped by post-fire establishment and natural succession (Figure 32). Composite uncertainty was estimated by collective expert knowledge uncertainty (*VL*=very low; *L*=low; *H*=high; *VH*=very high) and uncertainty of individual expert knowledge (*L*=low; *M*=medium; *H*=high) assessed earlier (see Sections 3.6 and 3.7). Collective expert knowledge uncertainty and individual expert uncertainty in knowledge were combined using the rank-weight matrix (see Figure 11) to derive the levels of composite expert uncertainty. The resulting levels of uncertainty assigned to rules were low, medium, and high, as illustrated in Figure 32. For post-fire establishment, four transition rules were in low, 13 in medium, and 16 in high uncertainty categories. For natural succession, one transition rules was in low, five in medium, and 29 in high uncertainty categories.

a)

Individual expert uncertainty \ Among -expert variability	VL	L	H	VH
L	2	0	0	0
M	2	0	0	0
H	13	12	4	0

b)

Individual expert uncertainty \ Among -expert variability	VL	L	H	VH
L	0	0	1	0
M	0	1	2	0
H	4	10	14	3

Figure 32. *The number of transition rules in categories of composite expert uncertainty, derived from individual expert confidence and perceived complexity in forest succession knowledge for (a)* post-fire establishment *transition rules and (b)* natural succession *transition rules in the Northwest Region. Letters indicate the levels of among-expert variability and individual-expert knowledge uncertainty. The numbers in each cell indicate the number of transition rules for the row (individual expert uncertainty)-column (collective expert uncertainty) combination. Collective expert uncertainty is* VL=*very low;* L=*low;* H=*high;* VH=*very high and individual expert uncertainty is* L=*low;* M=*medium;* H=*high. Levels of composite uncertainty are low uncertainty (dark grey), medium uncertainty (light gray), and high uncertainty (white).*

The composite uncertainty level assigned to each rule is shown Figure 33, where the rules are ordered according to priority ranking (as explained in the methods section). Values assigned to uncertainty levels were 1 = low uncertainty, 2 = medium uncertainty, 3 = high uncertainty. For convenience, we used uncertainty level 0 to denote the six transition rules excluded for post-fire establishment and four transition rules for natural succession.

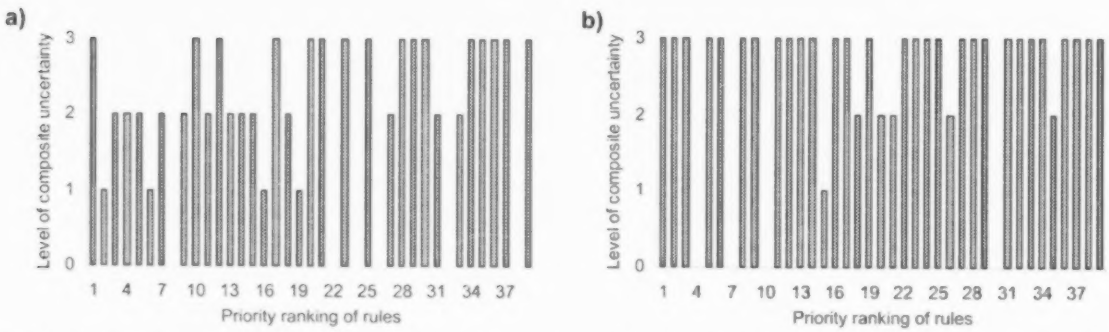

Figure 33. *The level of composite uncertainty for (a)* post-fire establishment *and (b)* natural succession *transition rules, as derived for experts in the Northwest Region. Priority ranking is in descending order of importance. Levels of composite uncertainty are 1 = low uncertainty, 2 = medium uncertainty, and 3 = high uncertainty. Composite uncertainty level 0 = unknown was used for transition rules that had to be excluded from the study.*

The summaries and analyses of levels of composite uncertainty assigned to rules were grouped by post-fire establishment and natural succession as illustrated in Figure 33. Measures of central tendency (mode, mean, and median) and shape (ordinal concentration indicates spread) of the overall composite uncertainty level and the distribution of composite uncertainty levels among transition rules are also provided.

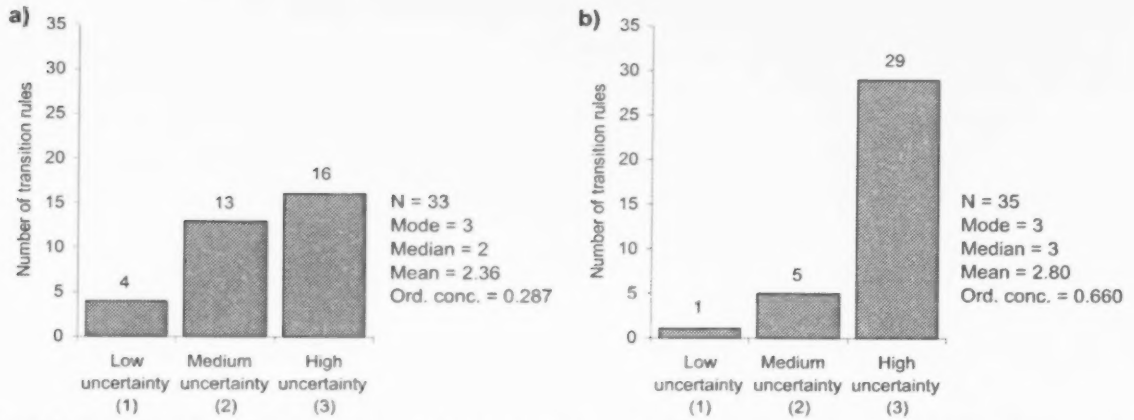

Figure 34. *Summaries of values of composite uncertainty assigned to rules on (a)* post-fire establishment *and (b)* natural succession *transition for experts in Northwest Region. (Numbers in parentheses indicate composite uncertainty levels and numbers above bars indicate the number of rules; Ord. conc. = normed ordinal concentration).*

3.8.2. Level of composite uncertainty in individual knowledge

Post-fire establishment

The ratio of numbers of observations in level 1 to level 3 was 0.25, indicating that the distribution of confidence about post-fire establishment transition rules was skewed left (Figure 34a). The large difference between the mode and the mean indicates that the left tail of the distribution must be relatively strong. The normed ordinal concentration indicates the dominance of the median level 3 over the two other levels and that level 1 must be weaker than levels 2 and 3.

Natural succession

The ratio of numbers of observations in level 1 to level 3 was 0.03, indicating that the distribution of confidence about natural succession transition rules was skewed left (Figure 34b). The left tail of the distribution cannot be very strong since the difference between the mean and mode is small. The normed ordinal concentration indicates a very strong dominance of the median level 3 and a very weak level 1.

Comparing post-fire establishment and natural succession

The ratio of numbers of observations in level 1 to level 3 was smaller than 1.00 for both post-fire establishment and natural succession indicating skewness to the left. The larger value of the normed ordinal concentration for composite uncertainty of natural succession knowledge compared to post-fire establishment indicates a stronger concentration of observations in level 3 for natural succession.

Conclusions

Uncertainty tends to be medium to high for knowledge about post-fire establishment and tends to be high for knowledge about natural succession. A summary of results that led to the final composite uncertainty in Northwest Region is illustrated in Figure 35.

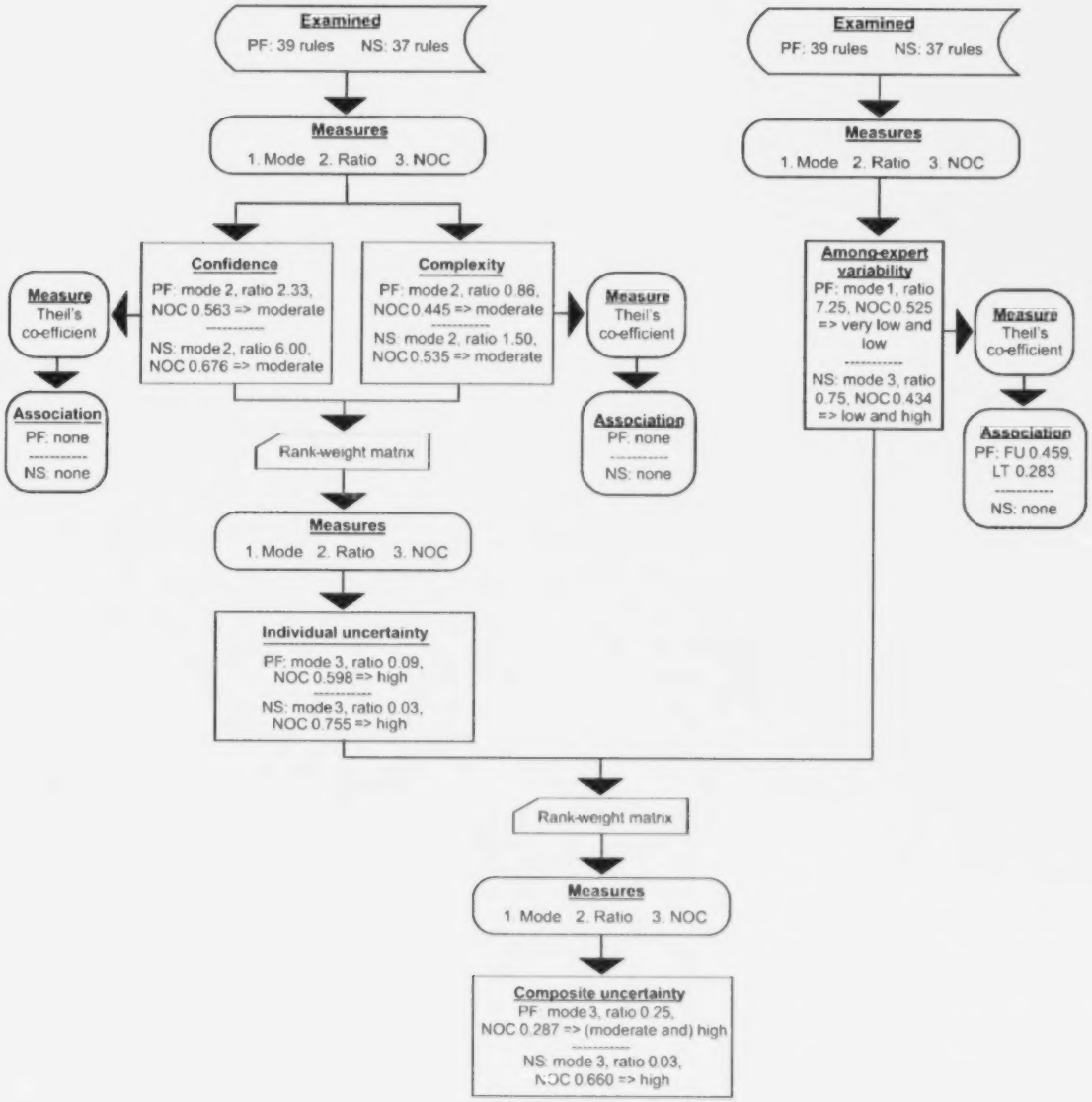
Examined
PF: 39 rules NS: 37 rules
Measures
1. Mode 2. Ratio 3. NOC
Confidence
PF: mode 2, ratio 2.33, NOC 0.563 => moderate
NS: mode 2, ratio 6.00, NOC 0.676 => moderate
Complexity
PF: mode 2, ratio 0.86, NOC 0.445 => moderate
NS: mode 2, ratio 1.50, NOC 0.535 => moderate
Measure
Theil's co-efficient
Association
PF: none
NS: none
Measure
Theil's co-efficient
Association
PF: none
NS: none
Rank-weight matrix
Measures
1. Mode 2. Ratio 3. NOC
Individual uncertainty
PF: mode 3, ratio 0.09, NOC 0.598 => high
NS: mode 3, ratio 0.03, NOC 0.755 => high
Examined
PF: 39 rules NS: 37 rules
Measures
1. Mode 2. Ratio 3. NOC
Among-expert variability
PF: mode 1, ratio 7.25, NOC 0.525 => very low and low
NS: mode 3, ratio 0.75, NOC 0.434 => low and high
Measure
Theil's co-efficient
Association
PF: FU 0.459, LT 0.283
NS: none
Rank-weight matrix
Measures
1. Mode 2. Ratio 3. NOC
Composite uncertainty
PF: mode 3, ratio 0.25, NOC 0.287 => (moderate and) high
NS: mode 3, ratio 0.03, NOC 0.660 => high

Figure 35. *A summary of the results from data analyses of the components of composite uncertainty in forest succession knowledge of individual experts in Northwest Region (PF= post-fire establishment transition rules, NS= natural succession transition rules, Ratio= ratio of numbers of observations in extreme levels (low:high), NOC= normed ordinal concentration, FU= forest unit, LT= leaf type, MOI= moisture regime, NUT= nutrient regime).*

3.9 Summary of results about expert knowledge uncertainty of forest succession and its possible sources

The overall degree of uncertainty associated with expert knowledge of forest succession was generally high in both regions, and especially so for natural succession. However, variability in uncertainty in knowledge among forest succession transition rules was considerable. For example, a bimodal distribution of expert group knowledge uncertainty (most transition rules in low or high degree categories, but few in medium) was evident for both post-fire establishment and natural succession in the Northeast Region. This dual-modality may be due to the correlation between expert's confidence about knowledge of transition rules and their perceived level of complexity (low confidence associated with high complexity and vice-versa). On the other hand, individual expert's knowledge uncertainty was mostly high for both transition rule types in the Northwest Region, resulting from the combination of medium confidence and complexity. Composite knowledge uncertainty of post-fire establishment in the Northwest Region was medium to high because of the high level of agreement among experts (leading to low collective uncertainty). For natural succession, however, collective uncertainty was low to high, which, in combination with high individual uncertainty, led to more transition rules with high composite uncertainty. These general findings are summarized in Table 23.

Table 23. *Overview of levels of uncertainty in expert knowledge about forest succession and its components for Northeast (NE) and Northwest (NW) Regions. Values in parentheses are percentages of expert-reviewed transition rules in each level.*

Region	Succession type	Confidence	Complexity	Uncertainty	Collective uncertainty	Composite uncertainty
NE	Post-fire establishment	Moderate (44%) to high (47%)	Medium (71%)	Low (47%) or high (53%)	NA[1]	
	Natural succession	Moderate (61%) to high (31%)	Low (33%) to medium (67%)	Low (31%) or high (61%)		
NW	Post-fire establishment	Moderate (74%)	Medium (67%)	High (85%)	Very low (52%) or low (36%)	Medium (39%) or high (48%)
	Natural succession	Moderate (81%)	Medium (73%)	High (89%)	Low (31%) or high (49%)	High (83%)

[1] Collective uncertainty and composite uncertainty could not be estimated in Northeast Region. See methods for details.

The estimates of confidence, perceived complexity, and collective uncertainty in forest succession knowledge were associated with some characteristics of transition rules. Among these, forest unit classification was most frequently significantly associated with the components of uncertainty, followed by leaf type, moisture regime, and nutrient regime. Of the various components of uncertainty, perceived complexity was most frequently associated with transition rule characteristics, followed by expert confidence. Collective uncertainty could not be included in this comparison, since it could not be quantified following the group consensus approach in the Northeast Region. More significant associations between transition rule characteristics and uncertainty components were found following the group consensus approach in the Northeast Region, than following the individual-based approach in the Northwest Region. Significant associations of transition rule characteristics with uncertainty components are summarized in Table 24.

Table 24. *Significant associations of components of uncertainty in expert knowledge about forest succession with characteristics of transition rules for Northeast (NE) and Northwest (NW) Regions (non-significant associations are denoted by a dash).*

Region	Succession type	Transition rule characteristic			
		Forest unit	Leaf type group	Moisture regime	Nutrient regime
NE	Post-fire establishment	Confidence	–	–	–
	Natural succession	Confidence and complexity	Complexity	Complexity	Complexity
NW	Post-fire establishment	Collective uncertainty	Collective uncertainty	–	–
	Natural succession	–	–	–	–

[1] Collective uncertainty and composite uncertainty could not be estimated in Northeast Region. See methods for details.

Despite the significant association of the components of uncertainty with forest unit, no unifying pattern of the distribution of forest units over the levels of uncertainty components emerged. For some forest units (e.g., PJ1 for natural succession in the Northeast Region, Table 25), high confidence was related with low complexity, while for other forest units, low to medium confidence was related with low complexity (e.g., SB1 for natural succession in the Northeast Region, Table 25). In contrast, associations of complexity and collective uncertainty with leaf type group were clearer: transition rules for coniferous forest units were perceived to be less complex and collective uncertainty was lower than for hardwood and mixedwood forest units. Though not common, the associations of perceived complexity with site conditions suggest that on more extreme sites levels of uncertainty are lower: poor and organic (Table 12) as well as dry and saturated (Table 13) conditions were more often linked to lower complexity levels than mesotrophic and rich or mesic and wet conditions (Table 25). The frequency of significant associations of uncertainty components with transition rule characteristics (except for forest unit) was lower for post-fire establishment than for natural succession rules. This difference might be explained by a temporary decrease in the importance of local conditions for post-fire dynamics as compared to subsequent succession. The lower frequency of significant associations of uncertainty components with transition rule characteristics in the Northwest Region might also be the result of low variability in site conditions in the priority transition rules for that region and by more timid responses of individual experts compared to the group consensus responses. An overview of the distribution of transition rule characteristics over the levels of uncertainty components is shown in Table 25.

Table 25. *Overview of the distributions of transition rule characteristics over the levels of components of expert knowledge uncertainty of forest succession for Northeast (NE) and Northwest (NW) Regions. Only distributions for which significant associations between components of expert knowledge uncertainty and transition rule characteristics were found (see Table 24) are shown. Transition rule characteristics were classified by component levels according to the majority of transition rules (e.g., in Northeast Region, the majority of post-fire establishment rules starting with LC1 were rated low confidence). NA indicates no significant association and a dash indicates that no transition rule characteristic was classified in this component level.*

Region	Succession type	Knowledge uncertainty		Transition rule characteristic			
		Component [1]	Component level [2]	Forest unit	Leaf type group	Moisture regime	Nutrient regime
NE	Post-fire establishment	Confidence	Low	LC1			
			Medium	PJ2, SP1, SF1, MW1	NA	NA	NA
			High	SB1, PJ1, PO1, BW1, MW2			
	Natural succession	Confidence	Low	PJ2			
			Low-medium	SB1			
			Medium	SF1, BW1, MW1, MW2	NA	NA	NA
			Medium-high	SP1			
			High	PJ1, LC1, PO1			
		Complexity	Low	SB1, PJ1, LC1, SP1	-	Saturated	Poor, organic
			Low-medium	-	Conifer	-	-
			Medium	PJ2, SF1, PO1, BW1, MW1, MW2	Mixedwood, hardwood	Dry, mesic, wet	Mesotrophic, rich
NW	Post-fire establishment	Collective uncertainty	Very low	PjDom	Conifer		
			Very low-low	PjMx1, BwDom	-	NA	NA
			Low	SbDom, PoDom	Hardwood		
			High	BfDom, HrdMw	Mixedwood		

[1] Only elements of uncertainty for which significant associations with transition rule characteristics were found are shown
[2] Only non-empty element levels are shown, e.g., no forest unit or leaf type group was classified as having high complexity for natural succession in the Northeast Region, thus this level is not shown

4. Conclusions

In general, the workshop approach was effective in eliciting forest succession knowledge from experts and thus making it non-latent and explicit. Since forest cover transition rules are a common mode of expressing and applying forest succession knowledge in Ontario, we used these as the basis for the knowledge elicitation process. There are numerous such rules, however the fraction considered high priority, based on their economic importance or influence on the landscape at regional level, is relatively small. Our sample of elicited knowledge represented 60 to 80% of the regionally relevant forest cover transition rules and hence also the body of knowledge. The experts who participated in the knowledge elicitation process represented the regional-level expertise in the Northeast and Northwest regions. These participants represented a total of more than 300 years of collective experience at regional level. Overall, the quality and the quantity of knowledge elicited were substantial. During the knowledge elicitation process, we observed that experts had some difficulty in articulating their knowledge explicitly and unequivocally, sometimes could not generalize their local knowledge, and preferred to express their knowledge as a group although the intent was to seek individual knowledge. In particular, experts had more difficulty in expressing their perception of complexity of the succession process than their level of confidence in the knowledge. Use of the workshop approach for eliciting expert knowledge was not without its disadvantages: (1) garnering expert participation was challenging because of many competing demands for their time, and (2) the knowledge elicitation process itself was time consuming and thus not only practically difficult but also costly. As a result, our sample size of consulted experts was small and non-random, which may limit the inference base of the results.

Expert's assessment of succession knowledge with respect to their confidence and perceived complexity of processes was mostly middle-ground; the most frequent response was medium. Variability in their assessments were associated most commonly with forest unit classification, leaf type group, and then site conditions. The resulting uncertainty level of individual knowledge varied between the regions. In the northwest, it was high, and in the northeast was distinctly dichotomous, with equal proportions of knowledge in low and high levels of uncertainty. Collective uncertainty of expert knowledge, which was assessed only in the northwest, was lower but variable. Knowledge of post-fire establishment had lower uncertainty levels than natural succession. This was translated to higher levels of composite uncertainty in knowledge of natural succession than in post-fire establishment in the northwest. The relationship of knowledge uncertainty with individual forest units was complex and no unifying pattern emerged, but for coniferous forest units in general, uncertainty components tended to be lower compared to hardwood and then mixedwood forest units. The distribution of complexity levels also indicated that experts tended to be less uncertain about successional dynamics under more extreme site conditions, such as dry or saturated, or poor and organic sites, compared to under relatively moderate site conditions such as mesic or wet, or mesotrophic or rich sites. We note several caveats associated with these findings, especially in extrapolating the results. First, though the participating experts represented the available regional-level expertise, the sample size of experts was small and not random considering the total population of all experts on forest succession in Ontario. Extrapolation from our results to the total expert population must therefore be done with caution. Second, we examined only a small and non-random sample of succession knowledge. Therefore, though experts considered this sample to be of high priority, statistical inference from our results to transition rules that we did not examine is not appropriate. Finally, we adopted a prudent approach in associating 'medium' responses, especially for expert confidence, with high uncertainty. We acknowledge that other approaches to the interaction of confidence and complexity, or individual and collective uncertainty, might produce different results. However, given the present context, it is appropriate to use our findings and conclusions as first insights and testable hypotheses of expert knowledge uncertainty.

In summary, we successfully elicited latent knowledge of two groups of experts in boreal forest succession about post-fire establishment and natural succession dynamics. Only through such a process of knowledge elicitation, can expert knowledge become explicit and its uncertainty assessed. Overall, we found that uncertainty was high, though variable. This finding is congruent with recent policy documents (OMNR 2004b, Sobze et al. 2006) that state that the knowledge of boreal forest succession in Ontario may not be adequate for several aspects of forest resource management. In addition to discovering the state of knowledge uncertainty, we associated some factors with variation in the levels of uncertainty of succession knowledge. Our results have implications for forest management in Ontario: if forest management is based on uncertain knowledge of forest succession and this knowledge uncertainty is ignored, the effectiveness of management activities may be decreased since management may be planned without full knowledge of the basic succession dynamics and less suitable management activities may perpetuate errors through the system. For policy development this means that (i) research that reduces knowledge uncertainty of boreal forest succession should be supported, and (ii) in areas where knowledge uncertainty cannot be reduced, it should be explicitly incorporated into forest management.

As mentioned at the outset, this report documents the first phase of a larger research study. The next steps in this research plan involve integrating reviewed expert knowledge with published literature to formulate unified and falsifiable hypotheses followed by tests of those with empirical observations. By explicitly identifying the uncertainty in specific areas of expert knowledge and some factors that contribute to that uncertainty first, these research steps can be better focused to improve the state of knowledge of forest succession in Ontario and its defensibility in applications.

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Appendices

Appendix I.

Timetable of major activities during planning and implementation of the expert workshops on boreal forest succession knowledge in MNR's Northeast (NE) and Northwest (NW) regions.

Date	Activity
December 8, 2005	Received agreement from NE and NW regional partners to participate in workshop phase of study
December 16, 2005	E-mailed draft expert workshop proposal to regional partners
January 16, 2006	Received comments on draft expert workshop proposal from NE region
February 3, 2006	Received comments on draft expert workshop proposal from NW region
February 6, 2006	Met with regional partners to co-ordinate logistics and next steps for NE region expert workshop, Timmins
February 8, 2006	Met with regional partners to co-ordinate logistics and next steps for NW region expert workshop, Thunder Bay
March 10, 2006	Invited regional experts to participate in NW workshop
March 2006	Invited regional experts to participate in NE workshop
March 31, 2006	Received list of priority transition rules from NW region
April 12, 2006	Conducted trial workshop with NE and NW regional partners, Sault Ste. Marie
April 19-20, 2006	Conducted first expert workshop NW Region, Thunder Bay
April 25, 2006	Received list of priority transition rules from NE region
May 10, 2006	Conducted first expert workshop NE Region, Timmins
May 11, 2006	Conducted second expert workshop NW region, via net-meeting
June 6, 2006	Conducted second expert workshop NW region, Timmins
August 9, 2006	Received data on additional reviewed rule sets from NE region

Appendix II.

Main steps of the standard procedure used to guide experts through the expert knowledge elicitation process during the expert workshops.

1. General

During each expert workshop, the knowledge elicitation process was preceded by an instruction phase. This was to familiarize experts with the specific workshop goals, the general tasks and questions they would be asked to complete, and the specific tools they would be using. Knowledge elicitation followed the brief instruction phase.

During the knowledge elicitation phase, experts navigated through a windows-based electronic questionnaire tool. The tool provided standardized visualization, capture, and management of expert knowledge about forest succession, grouped by:

(i) post-fire establishment transition rules,
(ii) natural succession transition rules, and
(iii) canopy ageing transition rules.*

For each, experts could review the available expert knowledge formulated as suggested rules and were asked to confirm or to refine them. Additionally, they were asked to estimate the variability of the rules and their level of confidence in the quantified knowledge (see section 2.1.1.). The standard order for review of transition rules was post-fire establishment followed by natural succession and canopy ageing.

Experts were asked to review all three rule types for all combinations of forest unit, ecogeographical unit, soil moisture regime, and soil nutrient regime as specified in the predetermined priority lists (see section 2.2.3.), beginning with the highest priority rule. Only after reviewing all three transition rule types in one combination did experts proceed to the next combination. Ideally, experts then proceeded until all combinations in the priority list were reviewed, which ended the knowledge elicitation phase.

Following is a description of the main steps involved in the standard protocol of knowledge elicitation. These steps describe the review of all three rule types for one combination of forest unit, ecogeographical unit, soil moisture regime, and soil nutrient regime.

2. Standard protocol

1. After selecting the relevant transition rule characteristics (ecogeographical unit, soil moisture regime, and soil nutrient regime) specified in the priority list of transition rules, experts began with a general evaluation of a visualization of the overall network of post-fire transition rules (Figure I). This step allowed the experts to see the rule being reviewed in the larger context of all possible post-fire dynamics for this combination of ecogeographical unit and soil moisture and nutrient regime.

*Knowledge about canopy ageing rules was elicited during the workshops but is not reported here due to discrepancies between the conceptualization of the canopy ageing process and experts' understanding of the process, which became apparent only after the workshops.

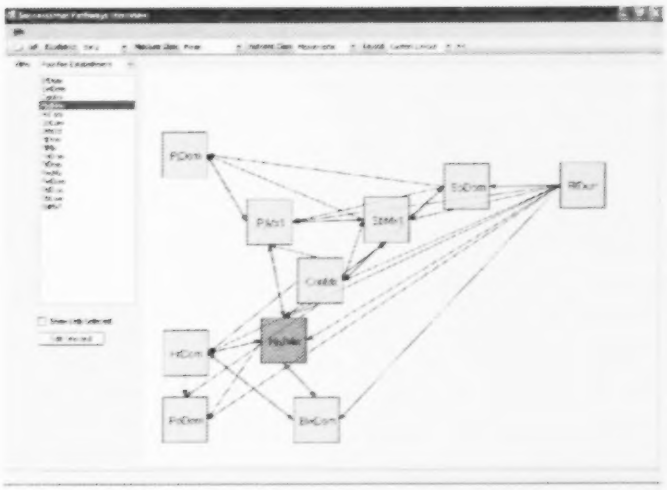

Figure I. *Visualization of a network of suggested post-fire establishment transition rules based on available expert knowledge. As an example, ecodistrict 3W-2 in Northwest Region was chosen as ecogeographical unit, and mesic and mesotrophic were chosen as soil moisture and nutrient regimes, respectively. The boxes represent forest units. Forest units that only are self-replacing, i.e., do not interact with other forest units, were not shown. Arrows indicate possible pathways between forest units and the direction of the transitions. The spatial position of the forest unit boxes approximated a light-demanding/shade-tolerant gradient (horizontal), and a deciduous/ coniferous gradient (vertical). The highlighted box indicated the forest unit selected for transition rule review. (Forest unit codes are explained in Table 2.)*

2. After the general evaluation of the overall rule network, experts proceeded with their review of the specific transition rule. Experts could first view additional information about the rule in figure and table format, to form an overall picture of the circumstances under which this rule applied (Figures II and III).

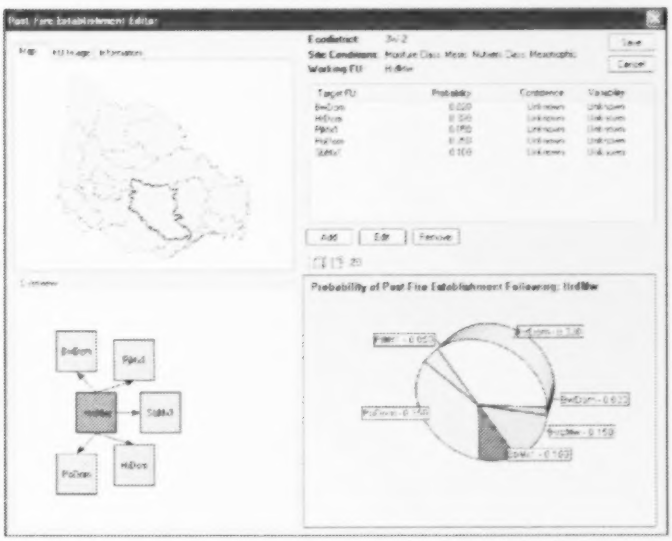

Figure II. *An example of the post-fire establishment transition rule editor screen, which provided information about transition rules as follows: (i) top left, the ecogeographical unit, the visual appearance of the originating forest unit, the species composition of the originating forest unit, and the site conditions (see Figure III), (ii) bottom left, a part of the transition rule network from the previous screen (Figure I) with the originating forest unit at its centre, (iii) top right, a tabular representation of probabilities of transitions to receiving forest units, confidence, and variability of transition probabilities, and (iv) bottom right, a pie diagram of transition probabilities. (Forest unit codes are explained in Table 2 of the main text.)*

This included information about the location of the ecogeographical unit (Map), the visual appearance of the originating forest unit (FU Image), the species composition of the originating forest unit, and the associated site conditions (Information). In Figure II, the window on the bottom left showed part of the transition rule network from the previous screen with the originating forest unit at its centre (only transitions originating from the forest unit being reviewed were shown). Multiple transition steps or transitions from other forest units to the selected forest unit were not shown. The window on the top right provided a tabular representation of the probability of each transition to all possible receiving forest units, as well as the expert's confidence, and the variability of the transition probability. Initially, the transition probabilities were set to the suggested rule values while confidence and variability were set to a default values (unknown). Self-replacement of the originating forest unit was not included. The window on the bottom right showed the probabilities of replacement of the originating forest unit as a pie diagram. Only this window provided the probability of self-replacement of the forest unit being reviewed.

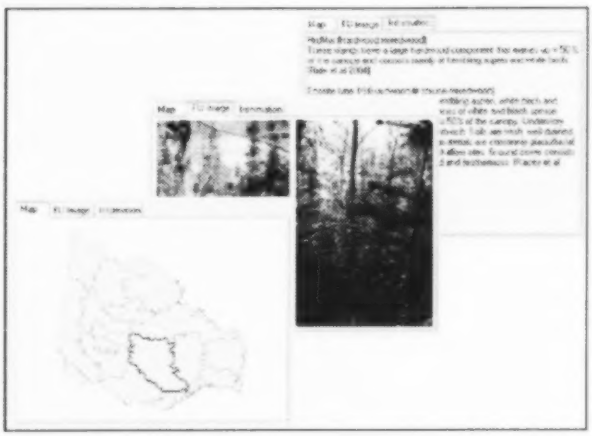

Figure III. *The stacked windows at the top left of the post-fire establishment transition rule editor screen (Figure II) provided information about the location of the ecogeographical unit, the general visual appearance of the originating forest unit and its species composition, and the site conditions applicable to the transition rule to be reviewed.*

3. Once the experts had gathered enough supporting information, they reviewed the transition rule. First, they decided whether to confirm or modify the suggested rule. If they confirmed the suggested rule, they left it as is and estimated the variability of each transition and their confidence that the information given for each transition was correct. To record these, experts chose from two drop down menus, where variability and confidence were presented as ordered-category items with three levels (high, medium, low) plus the default option (unknown) (Figure IV).

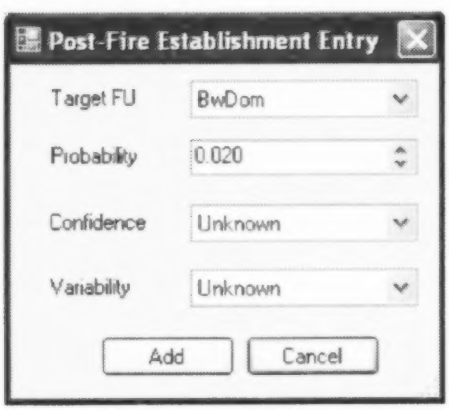

Figure IV. *In the post-fire establishment transition rule entry menu, transition rules could be edited using drop down menus. Target forest units (FU) could be added and associated transition probabilities, confidence, and variability values entered.*

If the experts modified the suggested rule, they first decided whether to change the group of receiving forest units (Target FU) by adding or deleting forest units from the list and then whether to change the transition probabilities to these forest units. After changing the group of receiving forest units and their transition probabilities, experts recorded the levels of variability and their confidence as described earlier. After all required values were entered, data were saved and experts returned to the main screen.

4.The experts proceeded with an evaluation of the overall network of natural succession transition rules (Figure V). Again, the initial step provided an overview of the natural succession rule being reviewed in the larger context of all possible transitions under the specified set of conditions.

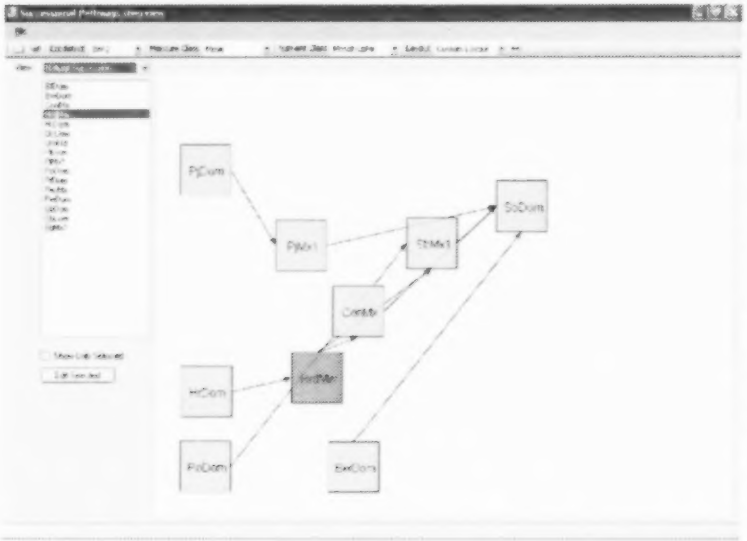

Figure V. *Visualization of a network of suggested natural succession transition rules based on available expert knowledge. As an example, ecodistrict 3W-2 in Northwest Region was chosen as ecogeographical unit, and mesic and mesotrophic were chosen as soil moisture and nutrient regimes, respectively. The boxes represent forest units. Forest units that are only self-replacing, i.e., do not interact with other forest units, were not shown. Arrows indicate possible pathways between forest units and the direction of the transitions. The spatial position of the forest unit boxes approximated a light-demanding/shade-tolerant gradient (horizontal), and a deciduous/coniferous gradient (vertical). The highlighted box indicated the forest unit selected for transition rule review. (Forest unit codes are explained in Table 2 of main text.)*

5. Following the general evaluation of the overall network of natural succession transition rules, experts could view additional information about the rule to be reviewed. As for the post-fire establishment rules, this information was presented in figure and table format (Figure VI).

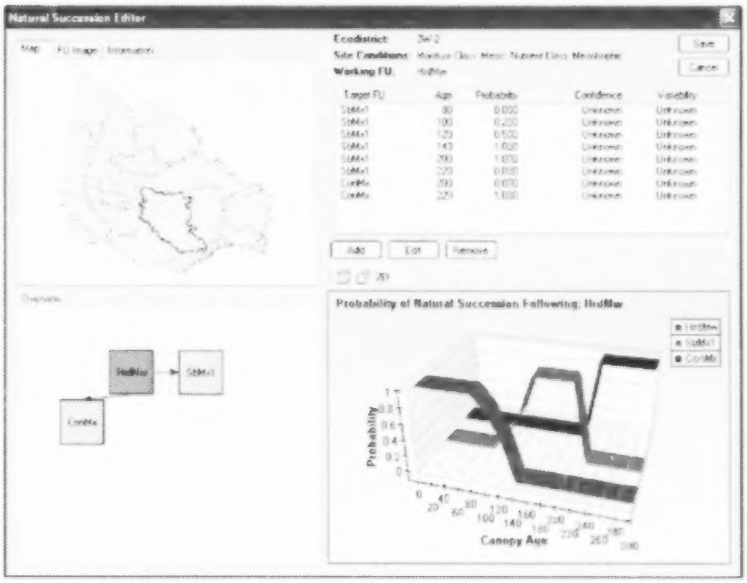

Figure VI. *The natural succession transition rule editor screen provided information as follows: (i) top left, the ecogeographical unit, the visual appearance of the originating forest unit, the species composition of the originating forest unit, and the site conditions, (ii) bottom left, a part of the transition rule network from the previous screen (Figure V) with the originating forest unit at its centre, (iii) top right, specified by the canopy age of the originating forest unit, a table of transition probabilities to receiving forest units, and confidence and variability of the transition probabilities, and (iv) bottom right, a line chart of transition probabilities specific for canopy age of the originating forest unit. (Forest unit codes are explained in Table 2 of the main text.)*

The left-hand windows provided the same information as that provided for post-fire succession rules as explained above. On the top right, tabular information was given of the temporal dynamics of the natural succession rule, specified for each receiving forest unit. Each entry represents a turning point or inflection point of a transition probability curve as a function of the age of the originating forest unit (Canopy age). It gives the name of the receiving forest unit (Target FU), the age of the originating forest unit, the transition probability, the expert's confidence, and the transition probability variability. Initially, the ages and transition probabilities showed the suggested rule while confidence and variability were set to a default value (unknown). Self-replacement of the forest unit was not shown.

On the bottom right, the temporal dynamics of the natural succession rule was shown graphically as a line diagram with the turning or inflection points from the table above connected by straight lines. The canopy age of the originating forest unit was given on the x-axis and transition probability on the y-axis. Only this window showed self-replacement of the originating forest unit.

6. When experts had gathered enough supporting information, they reviewed the transition rule and decided whether to confirm or modify the suggested rule. If they confirmed the suggested rule, they left it as is and estimated the variability of each transition probability and their confidence that the information given for each transition probability was correct. To record the levels of variability and confidence, they chose from two drop down menus, where variability and confidence were presented as ordered-category items with three levels (high, medium, low) plus an additional default option (unknown) (Figure VII).

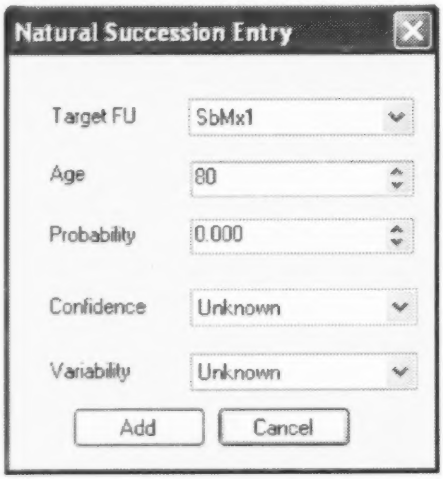

Figure VII. *In the natural succession transition rule entry menu, transition rules could be edited in drop down menus. Target forest units (FU) could be added and associated canopy ages, transition probabilities, confidence, and variability values could be entered.*

If the experts decided to modify the suggested rule, they first decided whether to change the group of receiving forest units (Target FU) by adding or deleting forest units from the list and then whether to change the ages or transition probabilities that represented the turning or inflection points of the transition probability curves. After changing the group of receiving forest units, ages, and transition probabilities, experts recorded the levels of variability and their confidence as described earlier. After all required values were entered, data were saved and the experts returned to the main screen.

7. The experts proceeded by evaluating a visualization of the canopy ageing rule for the relevant forest unit, specified by moisture regime but over all nutrient regimes (Figure VIII).

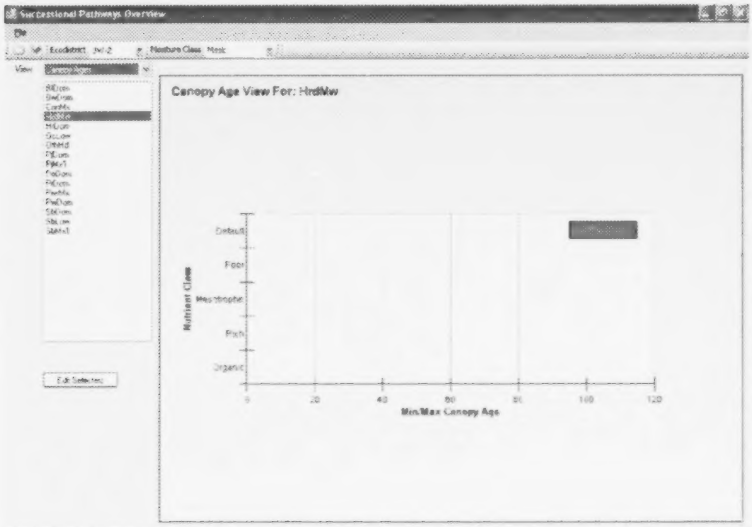

Figure VIII. *Sample visualization of canopy ageing rules. Horizontal bars indicated the minimum and maximum canopy age of the selected forest unit. Minimum canopy age was defined as the canopy age of a stand when it has succeeded from another forest unit to the selected forest unit. Maximum canopy age was defined as a stand's age when age-related canopy break-up of the selected forest unit occurs. Default minimum and maximum canopy ages were provided using information from suggested rules. (Forest unit codes are explained in Table 2 of the main text.)*

8. Following the general evaluation of the ageing rules, the experts received additional information about the rule to be reviewed. As previously, this information was presented in figure and table format (Figure IX). The three stacked windows on the left (Figures III and IX) provided information about the location of the ecogeographical unit, the visual appearance of the originating forest unit, the species composition of the originating forest unit, and the site conditions.

9. On the right, the minimum and maximum canopy ages and estimates of the expert's confidence and the level of variability of the canopy ages were provided in tabular form. Initially, canopy ages represented the suggested rules while confidence and variability were set to a default value (unknown).

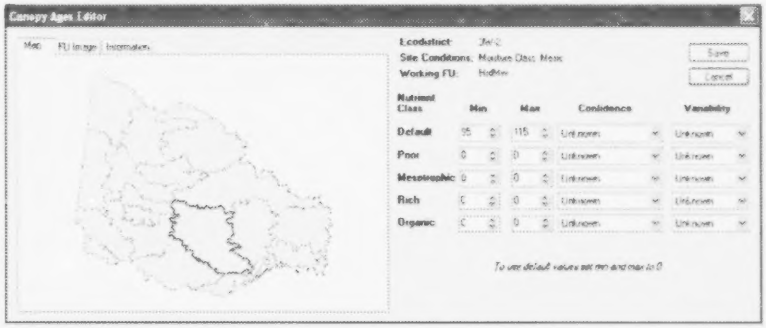

Figure IX. *The canopy aging rule editor screen provided information as follows: (i) left, the ecogeographical unit, the visual appearance of the originating forest unit, the species composition of the originating forest unit, and the site conditions, (ii) right, the minimum and maximum canopy ages, expert confidence, and the estimated variability of canopy age.*

Once the experts had gathered enough information, they confirmed or modified the suggested rule. If they confirmed the suggested rule, they left it as is and estimated the variability of canopy ages and their confidence that this information was correct. To record the levels of variability and confidence, experts chose from the drop down menus, where variability and confidence were presented as ordered-category items with three levels (high, medium, low) plus a default option (unknown) (Figure IX). If they modified the suggested rule, they first changed the canopy ages and then entered the estimated variability and confidence levels by selecting from the drop-down menus. After all required values were entered, data were saved and the experts returned to the main screen.

This finalized the review process of **one** transition rule set (post-fire, natural succession, and canopy ageing rules). This was repeated for all priority rule sets reviewed by each expert.

Appendix III.

Prioritized list of forest cover type–ecoregional unit–site condition combinations selected by forestry experts for the Northeast Region workshop. All combinations were reviewed by the expert group and included in the data analyses, except for those marked († - incompletely or not reviewed).

Priority rank	Forest cover type	Ecoregional unit	Moisture class	Nutrient class
1†	SB1	Non-Claybelt (NC)	saturated	organic
2	SB1	Claybelt (C)	saturated	organic
3	PO1	NC + C	mesic	mesotrophic
4	SF1	NC + C	mesic	rich
5	MW2	NC + C	mesic	rich
6	SF1	NC + C	wet	rich
7	MW2	NC + C	dry	mesotrophic
8	PJ1	NC + C	mesic	mesotrophic
9	LC1	Non-Claybelt	saturated	organic
10	LC1	Claybelt	saturated	organic
11	PJ1	NC + C	dry	mesotrophic
12	PJ1	NC + C	dry	poor
13	SP1	NC + C	mesic	mesotrophic
14	SP1	NC + C	dry	mesotrophic
15	BW1	NC + C	mesic	mesotrophic
16	MW2	NC + C	wet	rich
17	SP1	NC + C	wet	mesotrophic
18	MW2	NC + C	mesic	mesotrophic
19	SF1	NC + C	mesic	mesotrophic
20	SF1	NC + C	dry	rich
21	MW1	NC + C	dry	mesotrophic
22	MW1	NC + C	mesic	mesotrophic
23†	SB1	Non-Claybelt	wet	rich
24†	SB1	Claybelt	wet	rich
25	SP1	NC + C	mesic	rich
26	BW1	NC + C	dry	mesotrophic
27	PJ2	NC + C	dry	mesotrophic
28	PO1	NC + C	wet	rich
29	PO1	NC + C	mesic	rich
30	SF1	NC + C	dry	mesotrophic
31	SP1	NC + C	dry	poor
32	SP1	NC + C	wet	rich
33	MW2	NC + C	dry	rich
34	PJ2	NC + C	mesic	mesotrophic
35	SF1	NC + C	wet	mesotrophic
36	SP1	NC + C	dry	rich
37	BW1	NC + C	mesic	rich
38†	LC1	Non-Claybelt	wet	mesotrophic
39†	LC1	Claybelt	wet	mesotrophic
40†	MW2	NC + C	wet	mesotrophic
41	PJ1	NC + C	wet	mesotrophic
42†	PJ2	NC + C	dry	poor
43	PO1	NC + C	dry	Mesotrophic

Appendix IV.

Prioritized list of forest cover type–ecoregional unit–site condition combinations selected by forestry experts for the Northwest Region workshop. Combinations 1 to 39 were reviewed by the experts.

Priority rank	Forest cover type	Ecoregional unit	Moisture class	Nutrient class
1	HrdMx	3W-2	Mesic	Mesotrophic
2	PjDom	3W-2	Mesic	Mesotrophic
3	SbDom	3W-1	Mesic	Mesotrophic
4	SbDom	3S-5	Mesic	Mesotrophic
5	SbDom	3W-2	Mesic	Mesotrophic
6	PjDom	4S-5	Mesic	Mesotrophic
7	SbDom	3S-2	Mesic	Mesotrophic
8	PoDom	3W-2	Mesic	Mesotrophic
9	PjDom	3S-5	Mesic	Mesotrophic
10	SbDom	3W-5	Mesic	Mesotrophic
11	PjDom	4S-2	Mesic	Mesotrophic
12	SbDom	4S-2	Mesic	Mesotrophic
13	PjMx1	4S-5	Mesic	Mesotrophic
14	PjMx1	4S-1	Dry	Poor
15	PjMx1	3W-2	Mesic	Mesotrophic
16	PjDom	3S-2	Mesic	Mesotrophic
17	SbDom	3W-4	Mesic	Mesotrophic
18	PjDom	4S-1	Dry	Mesotrophic
19	PjDom	3W-1	Mesic	Mesotrophic
20	PjMx1	3W-1	Mesic	Mesotrophic
21	PjMx1	3S-5	Mesic	Mesotrophic
22	PoDom	4S-2	Mesic	Mesotrophic
23	HrdMx	3W-4	Mesic	Mesotrophic
24	HrdMx	3W-1	Mesic	Mesotrophic
25	SbDom	4S-3	Mesic	Mesotrophic
26	PjDom	4S-3	Dry	Mesotrophic
27	BwDom	3W-2	Mesic	Mesotrophic
28	PoDom	4S-5	Mesic	Mesotrophic
29	PoDom	4S-6	Mesic	Mesotrophic
30	SbDom	4S-1	Mesic	Mesotrophic
31	PoDom	4S-1	Mesic	Mesotrophic
32	SbMx1	4S-2	Mesic	Mesotrophic
33	PjDom	4S-6	Mesic	Mesotrophic
34	BfDom	3W-2	Mesic	Mesotrophic
35	PjMx1	4S-2	Mesic	Mesotrophic
36	SbDom	4S-5	Mesic	Mesotrophic
37	BwDom	3W-5	Mesic	Mesotrophic
38	PoDom	4S-4	Mesic	Rich
39	PoDom	3W-1	Mesic	Mesotrophic
40	PoDom	3W-4	Mesic	Mesotrophic

Appendix IV. *Continued*

Priority rank	Forest cover type	Ecoregional unit	Moisture class	Nutrient class
41	PjMx1	4S-3	Mesic	Mesotrophic
42	PoDom	3S-5	Mesic	Mesotrophic
43	BfDom	3W-4	Mesic	Mesotrophic
44	PjMx1	4S-6	Dry	Poor
45	PjDom	3W-4	Mesic	Mesotrophic
46	BwDom	3W-4	Mesic	Mesotrophic
47	BwDom	4S-5	Mesic	Mesotrophic
48	PoDom	3S-2	Mesic	Mesotrophic
49	PoDom	4S-3	Mesic	Rich
50	HrdMx	3W-5	Mesic	Mesotrophic
51	PjDom	4S-4	Mesic	Mesotrophic
52	PjDom	3W-5	Mesic	Mesotrophic
53	BwDom	3W-1	Mesic	Mesotrophic
54	BfDom	3W-1	Mesic	Mesotrophic
55	SbMx1	3W-4	Mesic	Mesotrophic
56	SbDom	4S-4	Mesic	Rich
57	BwDom	4S-2	Mesic	Mesotrophic
58	PjMx1	4S-4	Mesic	Rich
59	BwDom	4S-6	Mesic	Mesotrophic
60	SbDom	4S-6	Mesic	Mesotrophic
61	BwDom	4S-3	Mesic	Mesotrophic
62	BfDom	3W-5	Mesic	Mesotrophic
63	PoDom	3W-5	Mesic	Mesotrophic
64	SbDom	3S-1	Mesic	Mesotrophic
65	BwDom	4S-4	Mesic	Rich
66	BwDom	4S-1	Mesic	Mesotrophic
67	PjDom	3S-1	Dry	Mesotrophic
68	PoDom	3S-1	Mesic	Mesotrophic

Appendix V.

Technical information about Theil's uncertainty coefficient (Theil 1972 in SAS 2000), which was used as measure of association between elements of knowledge uncertainty and forest cover and site conditions of transition rules.

Theil's uncertainty coefficient is based on information theory and approaches variance as entropy. The uncertainty coefficient (*T*) for an independent variable (*I*) given a dependent variable (*D*), as a function of the entropy (*H*) is:

$$T(I \mid D) = \frac{H(X) + H(Y) - H(XY)}{H(Y)} \qquad (1)$$

$$H(X) = -\sum_{j}\left(\left(\frac{r_j}{n}\right)\ln\left(\frac{r_j}{n}\right)\right) \qquad (2)$$

$$H(Y) = -\sum_{k}\left(\left(\frac{c_k}{n}\right)\ln\left(\frac{c_k}{n}\right)\right) \qquad (3)$$

$$H(XY) = -\sum_{j}\sum_{k}\left(\left(\frac{n_{jk}}{n}\right)\ln\left(\frac{n_{jk}}{n}\right)\right) \qquad (4)$$

where *r* and *c* respectively indicate rows and columns in a contingency table; r_j is the row total (marginal) for row *j*; c_k is the column total (marginal) for column *k*; n_{jk} is the cell count in cell *j,k*; n is the total sample size; and *H(X)*, *H(Y)*, and *H(XY)* is the entropy of the row, column, and cell events, respectively. The entropy of events (i.e., the summed average uncertainty of the events) is a summary measure of the information that is contained in the events. In other words, the information received by observing an event *i* (u_i) is increasing with decreasing probability of this event, defined as (Shannon 1948):

$$u_i = -\ln p_i \qquad (5)$$

where p_i is the probability of event *i* and in the limit is approached by the frequency of event *i* ($f_i=n/n$). By multiplying the information from event *i* (u_i) with its frequency (f_i) and summing over all *i*, we get the entropy of the events (compare to 2).

The value of the uncertainty coefficient ranges from 0 to 1, where 0 indicates statistical independence of the two variables, and 1 indicates a perfect monotonic relationship between the two variables. An asymptotic test of the significance of the uncertainty coefficient is based on calculating a standardized test statistic *z*. *Z* is calculated as the ratio of the uncertainty coefficient with its approximate standard error and follows a standard normal distribution (SAS 2000).

Appendix VI.

Reviewed forest cover transition rule sets used in group uncertainty assessment in the Northeast

Table A. Post-fire establishment rules used in uncertainty assessment. (X = valid forest cover transitions)

Priority rank of rule	Origin forest unit	Destination forest unit										
		LH1	MW3	SB1	PJ1	LC1	PJ2	SP1	SF1	PO1	BW1	MW1
1	SB1			X		X		X				
2	SB1			X		X		X				
3	PO1									X	X	
4	SF1						X	X	X	X	X	X
5	MW2									X	X	X
6	SF1						X	X	X	X	X	X
7	MW2									X	X	X
8	PJ1				X			X				X
9	LC1	X	X	X		X						
10	LC1	X	X	X		X						
11	PJ1				X			X				X
12	PJ1				X			X				X
13	SP1				X		X	X		X	X	
14	SP1				X		X	X		X	X	
15	BW1									X	X	X
16	MW2									X	X	X
17	SP1				X		X	X		X	X	
18	MW2									X	X	X
19	SF1						X	X	X	X	X	X
20	SF1						X	X	X	X	X	X
21	MW1									X	X	
22	MW1									X	X	
23	SB1			X		X		X				
24	SB1			X		X		X				
25	SP1				X		X	X		X	X	
26	BW1									X	X	X
27	PJ2				X		X			X	X	X
28	PO1									X	X	
29	PO1									X	X	
30	SF1						X	X	X	X	X	X
31	SP1				X		X	X		X	X	
32	SP1				X		X	X		X	X	
33	MW2									X	X	X
34	PJ2				X		X			X	X	X
35	SF1						X	X	X	X	X	X
36	SP1				X		X	X		X	X	
37	BW1									X	X	X
38	LC1	X	X	X		X						
39	LC1	X	X	X		X						
40	MW2									X	X	X
41	PJ1				X			X				X
42	PJ2				X		X			X	X	X
43	PO1									X	X	

Table B. Natural succession rules used in uncertainty assessment. (X = valid forest cover transitions)

Priority rank of rule	Origin forest unit	Destination forest unit										
		MW3	SB1	PJ1	LC1	PJ2	SP1	SF1	PO1	BW1	MW1	MW2
1	SB1		X		X							
2	SB1		X		X							
3	PO1	X						X		X	X	X
4	SF1	X						X		X	X	X
5	MW2	X					X	X		X		X
6	SF1	X						X		X	X	X
7	MW2						X	X		X		X
8	PJ1					X					X	
9	LC1		X		X							
10	LC1		X		X							
11	PJ1					X					X	
12	PJ1					X					X	
13	SP1						X	X		X	X	
14	SP1						X	X		X	X	
15	BW1	X							X	X	X	X
16	MW2	X					X	X		X		X
17	SP1						X	X			X	X
18	MW2	X					X	X		X		X
19	SF1	X						X		X	X	X
20	SF1							X		X	X	X
21	MW1						X			X	X	
22	MW1						X			X	X	
23	SB1		X		X							
24	SB1		X		X							
25	SP1						X	X			X	X
26	BW1									X	X	X
27	PJ2						X				X	
28	PO1	X								X	X	X
29	PO1	X								X	X	X
30	SF1							X		X	X	X
31	SP1						X	X			X	
32	SP1						X	X			X	X
33	MW2						X	X		X		X
34	PJ2						X				X	
35	SF1	X						X		X	X	X
36	SP1						X	X			X	X
37	BW1	X							X	X	X	X
38	LC1		X		X							
39	LC1		X		X							
40	MW2	X					X	X		X		X
41	PJ1					X					X	
42	PJ2						X				X	
43	PO1									X	X	X

Appendix VII.

Reviewed forest cover transition rule sets used in individial uncertainty assessment in Northwest Region.

Table A. Post-fire establishment rule sets used in uncertainty assessment – Expert 1. (X = valid forest cover transitions)

Priority rank of rule	Origin forest unit	Destination forest unit									
		HrDom	PjDom	PjMx1	SbDom	BfDom	PoDom	BwDom	SbMx1	ConMx	HrdMx
1	HrdMx	X		X			X	X	X		X
2	PjDom		X	X							
3	SbDom			X	X				X		
4	SbDom		X	X	X				X	X	
5	SbDom		X	X	X				X	X	
6	PjDom		X	X							
7	SbDom		X	X	X				X		
8	PoDom						X				
9	PjDom		X	X						X	
10	SbDom				X				X	X	
11	PjDom		X	X							
12	SbDom		X	X	X				X	X	
13	PjMx1		X	X					X		X
14	PjMx1		X	X					X		X
15	PjMx1		X	X					X		X
16	PjDom		X	X							
17	SbDom		X	X	X				X	X	
18	PjDom		X	X							
19	PjDom		X	X						X	
20	PjMx1		X	X					X	X	
21	PjMx1		X	X					X	X	
22	PoDom						X				
23	HrdMx	X		X			X	X	X		X
24	HrdMx	X		X			X	X	X	X	X
25	SbDom		X	X	X				X	X	
26	PjDom						X				
27	BwDom	X						X			X
28	PoDom	X					X				X
29	PoDom	X					X				X
30	SbDom		X	X	X				X	X	
31	PoDom	X					X				
32	SbMx1		X	X	X				X	X	X
33	PjDom		X	X							
34	BfDom	X			X		X	X	X	X	X
35	PjMx1		X	X					X		
36	SbDom			X	X				X	X	
37	BwDom							X			X
38	PoDom						X				
39	PoDom	X					X				

Table B. Post-fire establishment rule sets used in uncertainty assessment – Expert 2. (X = valid forest cover transitions; * = rules excluded due to incomplete review)

Priority rank of rule	Origin forest unit	Destination forest unit									
		HrDom	PjDom	PjMx1	SbDom	BfDom	PoDom	BwDom	SbMx1	ConMx	HrdMx
1	HrdMx	X					X	X		X	X
2	PjDom		X	X							
3	SbDom			X	X				X		
4	SbDom		X	X	X				X	X	
5	SbDom		X	X	X				X	X	
6	PjDom		X	X							
7	SbDom		X	X	X				X		
8	PoDom						X				X
9	PjDom		X	X						X	
10	SbDom			X	X				X	X	
11	PjDom		X	X							
12	SbDom			X	X				X		
13	PjMx1		X	X					X		X
14	PjMx1		X	X					X		X
15	PjMx1		X	X					X		X
16	PjDom		X	X							
17	SbDom				X				X	X	
18	PjDom		X	X							
19	PjDom		X	X						X	
20	PjMx1		X	X					X		
21	PjMx1		X	X					X		
22	PoDom						X				
23	HrdMx	X		X			X	X	X	X	X
24	HrdMx	X		X			X	X		X	X
25	SbDom		X	X	X				X		
26	PjDom		X								
27	BwDom	X						X			X
28	PoDom						X				X
29	PoDom						X				X
30	SbDom		X	X	X				X		
31	PoDom						X				X
32	SbMx1		X	X	X				X	X	
33	PjDom		X	X							
34	BfDom				X				X	X	X
35	PjMx1		X	X					X		
36	SbDom		X	X	X				X	X	
37	BwDom							X		X	X
38	PoDom			X			X				X
39	PoDom	X					X			X	X

Table C. Post-fire establishment rule sets used in uncertainty assessment – Expert 3. (X = valid forest cover transitions)

Priority rank of rule	Origin forest unit	Destination forest unit									
		HrDom	PjDom	PjMx1	SbDom	BfDom	PoDom	BwDom	SbMx1	ConMx	HrdMx
1	HrdMx	X		X			X	X	X		X
2	PjDom		X	X							
3	SbDom			X	X				X		
4	SbDom		X	X	X				X	X	
5	SbDom		X	X	X				X	X	
6	PjDom		X	X							
7	SbDom		X	X	X				X		
8	PoDom						X				
9	PjDom		X	X						X	
10	SbDom				X				X	X	
11	PjDom		X	X							
12	SbDom		X	X	X				X	X	
13	PjMx1		X	X					X		X
14	PjMx1		X	X					X		X
15	PjMx1		X	X					X		X
16	PjDom		X	X							
17	SbDom		X	X	X				X	X	
18	PjDom		X	X							
19	PjDom		X	X						X	
20	PjMx1		X	X					X	X	
21	PjMx1		X	X					X	X	
22	PoDom						X				
23	HrdMx	X		X			X	X	X		X
24	HrdMx	X		X			X	X	X	X	X
25	SbDom		X	X	X				X	X	
26	PjDom						X				
27	BwDom	X						X			X
28	PoDom	X					X				X
29	PoDom	X					X				X
30	SbDom		X	X	X				X	X	
31	PoDom	X					X				
32	SbMx1		X	X	X				X	X	X
33	PjDom		X	X							
34	BfDom	X			X		X	X	X	X	X
35	PjMx1		X	X					X		
36	SbDom			X	X				X	X	
37	BwDom							X			X
38	PoDom						X			X	
39	PoDom	X					X				

Table D. Post-fire establishment rule sets used in uncertainty assessment – Expert 4. (X = valid forest cover transitions)

Priority rank of rule	Origin forest unit	Destination forest unit									
		HrDom	PjDom	PjMx1	SbDom	BfDom	PoDom	BwDom	SbMx1	ConMx	HrdMx
1	HrdMx	X					X	X			
2	PjDom		X	X							
3	SbDom			X	X				X		
4	SbDom		X	X	X				X	X	
5	SbDom		X	X	X				X	X	
6	PjDom		X	X							
7	SbDom		X	X	X				X		
8	PoDom						X				
9	PjDom		X	X						X	
10	SbDom		X	X	X				X	X	
11	PjDom		X	X							
12	SbDom		X	X	X				X	X	
13	PjMx1		X	X					X		X
14	PjMx1		X	X					X		X
15	PjMx1		X	X					X		X
16	PjDom		X	X							
17	SbDom		X	X	X				X	X	
18	PjDom		X	X							
19	PjDom		X	X						X	
20	PjMx1		X	X						X	
21	PjMx1		X	X					X		
22	PoDom						X				
23	HrdMx	X					X	X	X		X
24	HrdMx	X		X			X	X	X		
25	SbDom		X	X	X				X		
26	PjDom		X	X							
27	BwDom	X						X			X
28	PoDom	X					X				
29	PoDom	X					X				
30	SbDom		X	X	X				X	X	
31	PoDom	X					X				
32	SbMx1		X	X	X				X	X	X
33	PjDom		X	X							
34	BfDom	X		X			X	X	X	X	X
35	PjMx1	X	X	X					X		
36	SbDom		X	X	X				X	X	
37	BwDom	X						X			
38	PoDom						X				X
39	PoDom	X					X				

Table E. Natural succession rule sets used in uncertainty assessment – Expert 1. (X = valid forest cover transitions)

Priority rank of rule	Origin forest unit	Destination forest unit									
		HrDom	PjDom	PjMx1	SbDom	BfDom	PoDom	BwDom	SbMx1	ConMx	HrdMx
1	HrdMx					X				X	X
2	PjDom			X							
3	SbDom				X	X					
4	SbDom				X						
5	SbDom				X	X					
6	PjDom			X	X						
7	SbDom				X						
8	PoDom						X	X		X	X
9	PjDom			X					X		
10	SbDom				X						
11	PjDom			X					X		
12	SbDom				X	X					
13	PjMx1			X							
14	PjMx1			X	X						X
15	PjMx1								X		
16	PjDom			X					X		
17	SbDom				X	X				X	
18	PjDom		X	X					X		
19	PjDom			X					X		
20	PjMx1								X		
21	PjMx1								X		
22	PoDom										X
23	HrdMx					X				X	X
24	HrdMx					X				X	X
25	SbDom					X			X	X	
26	PjDom			X							
27	BwDom					X				X	X
28	PoDom						X				
29	PoDom										X
30	SbDom				X						
31	PoDom										X
32	SbMx1				X				X	X	
33	PjDom			X					X		
34	BfDom				X	X				X	
35	PjMx1								X		
36	SbDom				X	X				X	
37	BwDom									X	X
38	PoDom					X	X			X	
39	PoDom										X

Table F. Natural succession rule sets used in uncertainty assessment – Expert 2. (X = valid forest cover transitions)

Priority rank of rule	Origin forest unit	Destination forest unit									
		HrDom	PjDom	PjMx1	SbDom	BfDom	PoDom	BwDom	SbMx1	ConMx	HrdMx
1	HrdMx					X				X	
2	PjDom								X		
3	SbDom				X	X					
4	SbDom				X						
5	SbDom				X	X				X	
6	PjDom								X		
7	SbDom				X						
8	PoDom									X	
9	PjDom									X	
10	SbDom				X					X	
11	PjDom								X		
12	SbDom				X						
13	PjMx1								X		
14	PjMx1			X					X		
15	PjMx1								X	X	
16	PjDom								X		
17	SbDom				X					X	
18	PjDom			X					X		
19	PjDom								X		
20	PjMx1								X		
21	PjMx1								X		
22	PoDom				X						
23	HrdMx									X	
24	HrdMx									X	
25	SbDom				X					X	
26	PjDom			X							
27	BwDom					X				X	X
28	PoDom									X	X
29	PoDom									X	
30	SbDom				X						
31	PoDom									X	
32	SbMx1				X						
33	PjDom								X		
34	BfDom					X					
35	PjMx1								X		
36	SbDom				X						
37	BwDom				X			X		X	X
38	PoDom					X				X	
39	PoDom									X	

Table G. Natural succession rule sets used in uncertainty assessment – Expert 3. (X = valid forest cover transitions)

Priority rank of rule	Origin forest unit	Destination forest unit									
		HrDom	PjDom	PjMx1	SbDom	BfDom	PoDom	BwDom	SbMx1	ConMx	HrdMx
1	HrdMx					X		X		X	X
2	PjDom			X					X	X	
3	SbDom					X				X	
4	SbDom				X						
5	SbDom				X	X				X	
6	PjDom		X						X	X	
7	SbDom				X						
8	PoDom					X				X	
9	PjDom			X	X						
10	SbDom				X						
11	PjDom			X					X		
12	SbDom				X					X	
13	PjMx1								X		
14	PjMx1			X					X		
15	PjMx1								X	X	
16	PjDom			X							
17	SbDom									X	
18	PjDom			X							
19	PjDom			X							
20	PjMx1								X		
21	PjMx1								X		
22	PoDom										X
23	HrdMx									X	
24	HrdMx									X	
25	SbDom				X					X	
26	PjDom								X		
27	BwDom							X		X	X
28	PoDom										X
29	PoDom										X
30	SbDom				X				X		
31	PoDom										X
32	SbMx1				X						
33	PjDom			X							
34	BfDom									X	
35	PjMx1								X		
36	SbDom				X	X				X	
37	BwDom										X
38	PoDom									X	
39	PoDom	X									

Table H. Natural succession rule sets used in uncertainty assessment – Expert 4. (X = valid forest cover transitions)

Priority rank of rule	Origin forest unit	Destination forest unit									
		HrDom	PjDom	PjMx1	SbDom	BfDom	PoDom	BwDom	SbMx1	ConMx	HrdMx
1	HrdMx					X				X	X
2	PjDom			X					X	X	
3	SbDom								X		
4	SbDom				X						
5	SbDom				X	X				X	
6	PjDom								X	X	
7	SbDom				X						
8	PoDom	X				X				X	X
9	PjDom			X							
10	SbDom									X	
11	PjDom			X							
12	SbDom				X					X	
13	PjMx1								X	X	
14	PjMx1			X					X	X	
15	PjMx1								X	X	
16	PjDom			X							
17	SbDom									X	
18	PjDom			X							
19	PjDom			X					X		
20	PjMx1								X		
21	PjMx1								X		
22	PoDom										X
23	HrdMx									X	
24	HrdMx									X	
25	SbDom				X	X			X	X	
26	PjDom		X	X							
27	BwDom									X	X
28	PoDom	X									X
29	PoDom	X									
30	SbDom				X						
31	PoDom										X
32	SbMx1				X						
33	PjDom			X							
34	BfDom					X					
35	PjMx1								X		
36	SbDom				X	X				X	
37	BwDom										X
38	PoDom									X	
39	PoDom	X									

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